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Numerical Study on the Effect of an Annulus Injector on the Hydrodynamic Behavior of a Spray

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ABSTRACT

In the internal combustion engines geometry of the injector orifice has significant effect on the improving of the fuel spray characteristics. In the present paper, effect of a conical annulus injector with three different aspect ratios and three different divergence angles of the annulus orifice on the hydrodynamic behavior of a fuel spray have been investigated numerically. The conical annulus injector aspect ratio is the ratio of the height of the annulus cone to the diameter of its circular base. The geometry of the annulus conical injectors inspires this idea that this type of injectors could inject possible large amount of liquid fuel into a combustion chamber symmetrically and homogeneously. The CFD software AVL Fire has been employed for numerical simulation of diesel fuel spray evolution. Numerical results show that the annulus conical injectors inject liquid fuel with an approximately homogenous distribution of droplets in the combustion chamber in comparison with the conventional injectors. In this kind of injector, fuel has been uniformly distributed in the cylinder. Numerical results also show that the annulus injectors significantly increase the cone angle of the liquid fuel spray and decrease its penetration length.

Keywords: Annulus conical injector; CFD; AVL Fire; Spray; Homogenous distribution of droplets.

NOMENCLATURE

A	constant, standard setting A = 400	SMD	Sauer Mean Diameter
B	constant, standard setting B = 3	v	actual discharge velocity
C_3	constant, standard setting $C_3 = 1.17$	v_{rel}	relative velocity between liquid and gas
d	diameter of conventional injector orifice	X	ratio of air core to total area
Din	inner diameter of annulus injector	μ	liquid dynamic viscosity
D_{out}	outer diameter of annulus injector	ρ	liquid density
h	height of annulus injector orifice	α	divergence angle of the annulus orifice
l	height of conventional injector orifice	θ	half outer cone angle
ΔP	pressure difference		

1. INTRODUCTION

The fuel injection system in an internal combustion engine is believed to be the heart of the engine. This belief is due to the fact that proper performance of a fuel injection system in an internal combustion engine could decrease fuel consumption and pollutant emissions. Traditional injectors are mostly cylindrical and rarely are convergent or divergent with circular cross section. In the recent years in the attempts for achieving the fuel injection systems with a very high performance, the non-circular injectors have been under consideration of researchers. Among them Sharma, P., & Fang, T. (2015) investigated the hydrodynamic characteristics of liquid fuel spray resulted from a common rail fuel injector with a non-circular orifices experimentally. They have reported their experimental observations about the different effects of the circular and non-circular injectors on the hydrodynamic behavior of the liquid fuel sprays and have reported the differences between the results. Their results have shown that the liquid fuel sprays resulted from the injectors with a rectangular cross section have the greatest magnitude of the cone angle in comparison with sprays resulted either from the injectors with a circular cross section or the injectors with a triangular cross section. Sharma and Fang have also reported the results of their investigations on the effects of the injectors with a non-circular cross section on the breakup of the low pressure water jets (Sharma, P., & Fang, T. 2014). The experimental investigations in the case of having air or gaseous spray show that the cross section of these sprays have the similar shape to the shape of the injector's cross section but rotate at the characteristic angular rate of the injector geometry by moving downward along the axis of the sprays (Gutmark, E., Schadow, K. C., Parr, T. P., Hanson-Parr, D. M., & Wilson, K. J. 1989; Toyoda, K., & Hussain, F. 1989; Quinn, W. R. 1992). This is due to the self-induced Biot – Savart deformation of eddy rings with the non-uniform azimuthal curvature and the interaction between the stream-wise and azimuthal vortexes (Gutmark, E. J., & Grinstein, F. F. 1999; Drazin, P. G., & Reid, W. H. 1981). Yamamoto, H., & Niimura, K. (1995) have investigated the hydrodynamic behavior of the liquid fuel spray by employing a slit nozzle for obtaining a homogenous air-fuel mixture in the diesel internal combustion engines. They also observed the liquid fuel spray from the different sides, perpendicular and parallel to the slit orifice. They have reported that by employing a slit orifice they had not achieved a considerable improvement in air entrainment in comparison with the case of using a cylindrical nozzle because of having orifice cross section with a large hydraulic diameter. Kawamura, K., Saito, A., Kanda, M., Kashiwagura, T., & Yamamoto, Y. (2003) have used the spray hydrodynamic characteristics resulted from a slit nozzle for direct injection gasoline engines in order to establish some empirical correlations between them. They determined some empirical relation for the spray Sauter mean diameter (SMD) and penetration length. The annulus nozzles can be mentioned among the non-circular cross section nozzles which provide the hollow cone liquid fuel sprays. The annulus nozzles concentrate the spray droplets on the out surface of the spray's cone and produce hollow cone spray. The annulus nozzles have important applications in industrial processes, e.g. gas scrubbing, gas cooling, humidification in air handling units, cooling and disinfection in green house, poultry, disinfection of conveyors with alcohol, spraying of deodorant and dust suppression. In a hollow cone liquid fuel spray that has been resulted from the annulus nozzle, the liquid has been broken into the droplets that are heavily concentrated at the edges of the spray conical plume. In these hollow cone sprays, the cone angle can vary from 30 degrees to 170 degrees depending on the nozzle design (Park, K. S., & Heister, S. D. 2010; Sivakumar, D., Vankeswaram, S. K., Sakthikumar, R., Raghunandan, B. N., Hu, J. T. C., & Sinha, A. K. 2016; Nonnenmacher, S., & Piesche, M. 2000; Fan, Y., Hashimoto, N., Nishida, H., & Ozawa, Y. 2014).

The annulus injectors have been used in agriculture for spraying and irrigation. These types of injectors have also been employed in industry for cooling of hot surfaces and in pharmacy and medicine as spraying dryers (Lin, S. P. 2003; Dong, Q., Ishima, T., Kawashima, H., & Long, W. Q. 2013; Son, M., Yu, K., Radhakrishnan, K., Shin, B., & Koo, J. 2016; Son, M., Yu, K., Koo, J., Kwon, O. C., & Kim, J. S. 2015; Dressler, G., & Bauer, J. 2000; Eslamian, M., & Ashgriz, N. 2011; Ashgriz, N., Li, X., & Sarchami, A. 2011; Clark, C. J., & Dombrowski, N. 1972).

This brief review about the importance and wide range applications of the annulus injectors in the agriculture, industry, pharmacy and medicine clearly shows the reasons for our motivation in this research. This research presents a numerical investigation on the hydrodynamic characteristics of a liquid fuel spray in the internal combustion engines resulted from an annulus injector by using the CFD software AVL Fire. It should be noted that in the case of non-circular sprays, the primary and secondary breakup phenomena are different from the case of circular sprays. The annulus orifices could induce further instabilities during evolution of a spray. In this paper an annulus injector's effects on the hydrodynamic behavior of a fuel spray have been investigated numerically. The main advantage of an annulus injector is providing homogeneous and axisymmetric distribution of the fuel droplets inside the combustion chamber. In this type of injectors the spray plume is a hollow cone and consequently the large size fuel droplets which usually exist inside the spray core are not existed in the case of using conical annulus injectors. Therefore in the annulus injectors lack of large size fuel droplets and existence homogenous and axisymmetric distribution of the droplets in the combustion chamber lead to the improvement of the air/fuel mixture quality and consequently lead to a better combustion with less pollutant emissions.

2. GEOMETRY OF THE PROBLEM

Figure 1 illustrates the geometry of an annulus injector which has been proposed in this paper. Four different aspect ratios of h/D_{in} and three different divergence angles of the annulus orifice have been considered throughout this investigation

2.1 Theory of the Problem

Liquid sprays disintegrate a liquid flow to a large number of small droplets. The processes of fragmentation of the liquid flow into small droplets occur through two main breakups, which are known as the primary and the secondary breakups. The primary breakup of the liquid flow occurs at the instant of exiting of the liquid flow from the injector nozzle. In this process the liquid flow has been disintegrated into a number of small droplets with a diameter comparable to the diameter of the injector nozzle. As these droplets move with a high velocity in the gaseous ambient out of the injector nozzle, the aerodynamic forces of the gaseous ambient on the surfaces of these small liquid droplets cause occurring of Rayleigh-Taylor instability on the surfaces of the small droplets and consequently disintegrate them into smaller ones. The fragmentation of the small droplets into the smaller ones due to the aerodynamic forces of the gaseous

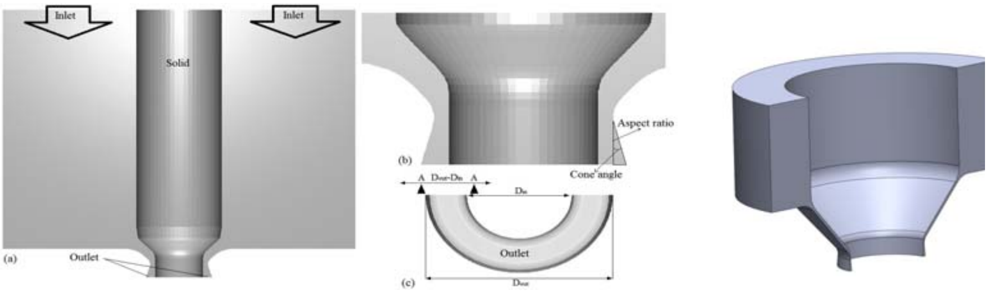


Fig. 1. Geometry of the proposed annulus injector.

ambient is called the secondary breakup of a liquid spray. During the primary and the secondary breakups of a liquid fuel spray, the diameter of the droplets along and close to the axial line of the spray are relatively larger than the diameter of the other droplets. These relatively large droplets along and close to the axial line of the spray may deteriorate combustion quality in an internal combustion engine and increase the pollutant emissions. Therefore the investigation carried out in this paper comes from the idea that by using an annulus injector, the plume of the resulted liquid fuel spray becomes a hollow cone and consequently does not contain relatively large droplets which are usually found along the axis of liquid sprays resulted from the traditional injectors with conical or cylindrical orifices. It is predicted that a liquid fuel spray with a hollow cone shape could provide a well homogenous air/fuel mixing. A better mixing of air/fuel in the combustion chamber of an internal combustion engine decreases the fuel consumption and the emission of the hazardous pollutants as well.

The liquid flow through the annulus injector and its upstream is a viscous liquid flow which could be cavitated if it is subjected to a certain value of the pressure tension. The Navier-Stokes equations governs the hydrodynamic behavior of the viscous liquid flow and the multi-fluid model has been employed for simulation of the cavitating mode of the liquid flow whenever it is required. The numerical simulation of the problem inside the injector and its upstream has been carried out by using the Eulerian-Eulerian approach. Whereas the hydrodynamic behavior of the liquid fuel spray inside the chamber containing compressed air have been carried out by using the Eulerian-Lagrangian approach.

For simulation of the primary breakup of the annulus liquid fuel spray at the exit of the nozzle inside the combustion chamber the model of the liquid sheet breakup has been selected in the AVL Fire CFD code. The model of the liquid sheet breakup is a semi-empirical model for the primary break-up of the liquid fuel spray which determines the thickness of the liquid fuel sheet, its velocity and length of the break-up. The thickness of the liquid fuel sheet at the exit of an annulus nozzle is determined as:

$$h = \left[\frac{A.12.m_2 \ .\mu_2}{\pi.\rho_1 \ .d_{out} .\Delta p} \ . \ \frac{(1+X)}{(1-X)^2} \right]^{0.5} \tag{1}$$

where X, is the ratio of the air core to the total area and has been given as:

$$X = \frac{(d_{out} - 2.h)^2}{d_{out}^2} \tag{2}$$

The velocity coefficient has been defined as:

$$K_v = \frac{v}{(2.\Delta p / \rho_1)^{0.5}} \tag{3}$$

and can be determined as:

$$k_v = \frac{C_2}{\cos\theta} . \left(\frac{(1-X)}{1+X} \right)^{0.5} \tag{4}$$

The breakup length of liquid sheet can be evaluated as:

$$B_L = B \ . \left[\frac{\rho_1 \ .\sigma \ .\ln\left(\dfrac{\eta}{\eta_0} \right) \ .h.\cos\theta}{\rho_0^2 \ . \ V_{rel}^2} \right]^{0.5} \tag{5}$$

2.2 Discretization

The liquid domain inside the nozzle is discretized into structured finite volumes. For obtaining grid independency for liquid fuel flow field inside the nozzle, three different number of cells have been chosen. The mass flow rate of the liquid fuel exiting from the nozzle has been considered as the criterion for the grid independency inside the injector. As it can be seen in Fig. 2 the first discretization of the injector by 19000 cells evaluates the mass flow rate of the liquid fuel exiting from the nozzle as about 0.0009kg/s. This figure also shows that the mass flow rate of the liquid fuel exiting from the nozzle at the second discretization of the computational domain by 45000 cells is about 0.00088 kg/s. Furthermore third discretization of the computational domain by 65000 cells for the two phase liquid fuel flow inside the nozzle determines the mass flow rate as about 0.00087 kg/s which is nearly the same magnitude obtained in the case of the second discretization. As a consequent the second discretization of the computational domain inside the injector has been selected as the verified discretization of the computational domain for the two phase liquid fuel flow which satisfies the grid independency of the problem.

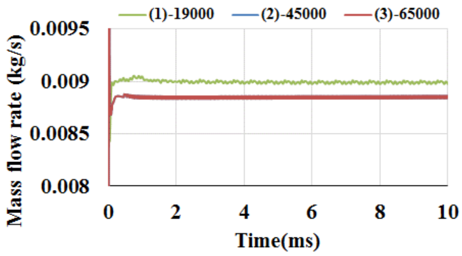


Fig. 2. Grid independency of the multiphase flow field.

Figure 3 represents the geometrical and physical discretization of the problem schematically.

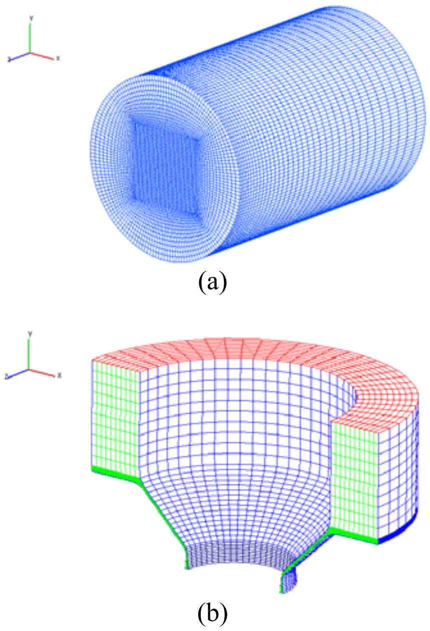


Fig. 3. Schematic representation of the geometrical and physical discretization of the problem.

2.2 Computational Implementation

The numerical simulation of the viscous liquid flow through the nozzle during the injection time and also the numerical simulation of the evolution of the spray plume have been carried out by employing the finite volume discretization method and by using the AVL Fire CFD code. The scenario for the numerical solution of the problem is such that the discretization of the liquid domain inside the injector nozzle has been carried out by using the Eulerian-Eulerian approach. The hydrodynamic characteristic of the liquid flow at the exit of the injector nozzle provide the inlet boundary condition for the numerical simulation of the spray evolution and its hydrodynamic behavior. Simulation of the problem outside the injector nozzle which includes the spray plume and its gaseous ambient has been carried out by employing the Eulerian-Lagrangian approach.

The boundary condition upstream the liquid domain inside the injector nozzle is the upstream pressure which is provided by the fuel pump and could vary with respect to time by following any specified fuel injection patterns. Since the fuel injection time has been assumed to be 1.5ms, then a constant time step equal to 0.001ms has been considered for the time historical advancement of the numerical solution of the problem.

3. RESULTS AND DISCUSSION

In this section, the effects of the annulus nozzle aspect ratio, the divergence angle of the nozzle annulus orifice and the mass flow rate of the liquid fuel exiting from the nozzle on the hydrodynamic behavior of the resulted spray has been investigated.

3.1 Effect of Nozzle Aspect Ratio on the Hydrodynamic Behavior of the Liquid Fuel Spray

The numerical investigations have been carried out in the five different cases with different aspect ratios. In the four cases of the numerical investigations the annulus injector has been assumed to be conical while in the fifth case it is assumed to be cylindrical. The upstream pressure and temperature of the injector have been assumed to be 60 MP and 293K respectively. The pressure and temperature at the downstream of the injector are 0.1MPa and 293.15K respectively and the fuel droplets have been subjected to the evaporation. Since the experimental results for the conical annulus injector have not been reported in the literature. Therefore, for validation of the numerical results of this investigation, the reported experimental results of Sharma, P., & Fang, T. (2015) for the case of one orifice, the traditional injector have been used under the same circumstances (Figs. 5a and 9a). Also two different patterns of the liquid fuel injection have been considered to show that in the proposed annulus injector nozzle it is possible to increase the mass flow rate of the fuel without deteriorating of the spray hydrodynamic behavior.

The upstream and downstream boundary conditions for the all five cases are the same which have been shown in tables 2 and 3.

The injection time indicates the time after the start of the fuel injection. Figures 3a to 3d illustrate the spray plume in the first, second, third and fourth cases of the first series of the numerical investigations at the injection times of 0.85ms and 1.2ms. Figure 3e shows the spray plume in the fifth

Table 1 Geometrical characteristics of the first series of the numerical investigations

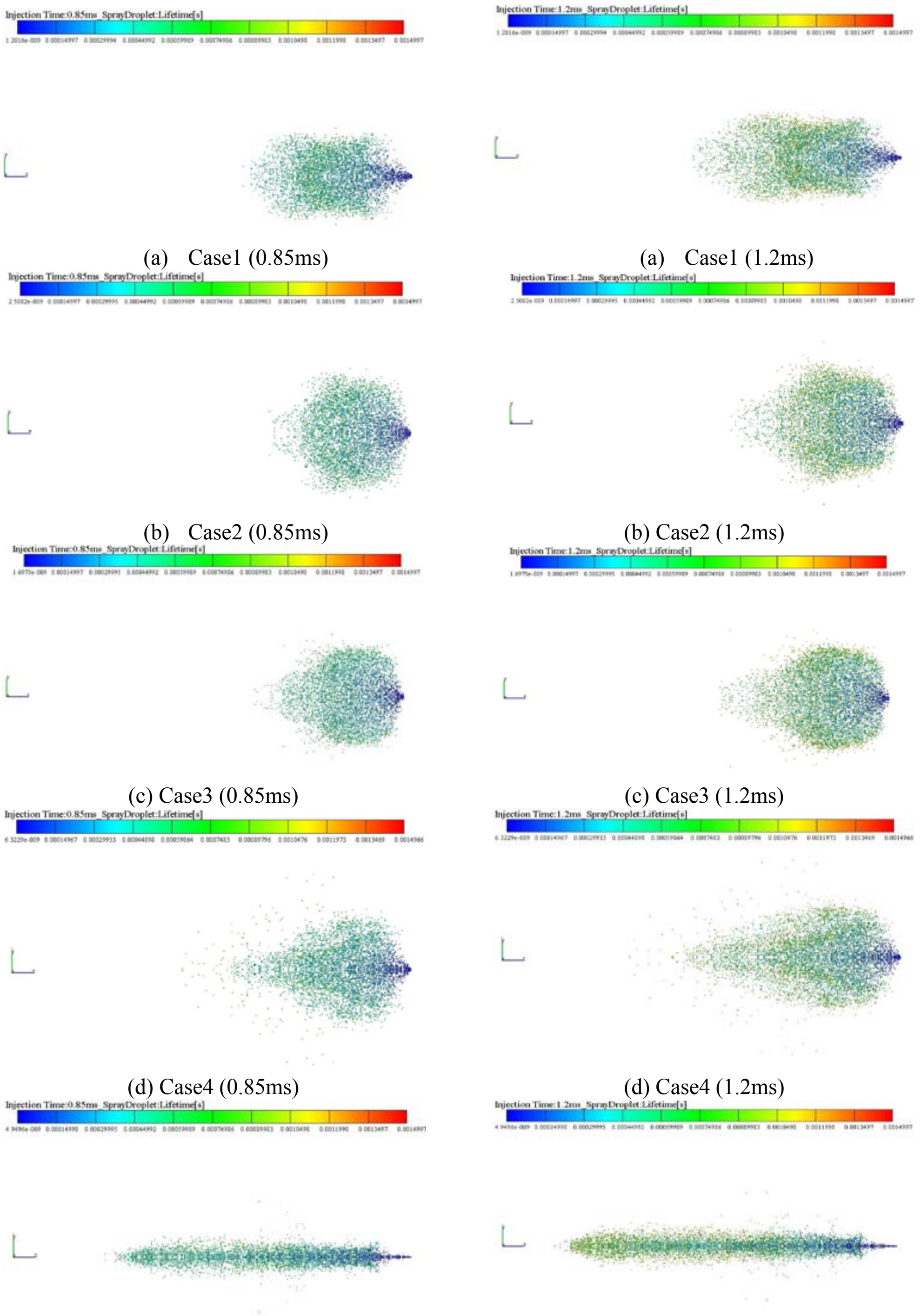
	d (mm)	Din (mm)	Dout (mm)	l (mm)	α(deg)
Case 1	-	1	1.02	0.1	10
Case 2	-	1	1.02	0.15	10
Case 3	-	1	1.02	0.2	10
Case 4	-	1	1.02	0.3	10
Case 5	0.165	-	-	0.7	-

Table 2 Upstream boundary conditions

Density	Dynamic viscosity	Inlet pressure	Outlet pressure
830kg/m3	0.00214Ns/m2	60MPa	0.1MPa

Table 3 Downstream boundary conditions

Density	Pressure	Temperature
1.2kg/m3	0.1MPa	293.15K



(a) Case1 (0.85ms)
(a) Case1 (1.2ms)
(b) Case2 (0.85ms)
(b) Case2 (1.2ms)
(c) Case3 (0.85ms)
(c) Case3 (1.2ms)
(d) Case4 (0.85ms)
(d) Case4 (1.2ms)
(e) Case5 (0.85ms)
(e) Case5 (1.2ms)

Fig. 4. The spray plume in the: a; first, b; second, c; third, d; fourth and e; fifth cases of the first series of the numerical investigations at the injection times of 0.85ms and 1.2ms.

case of the first series of the numerical investigations at the injection times of 0.85ms and 1.2ms.

Comparisons between Figs. 4a-4d show that, by having the same inlet and outlet pressure as boundary conditions and the same divergence angle of the annulus nozzle and by changing just the annulus nozzle's aspect ratio, the hydrodynamic behavior of the resulted sprays change dramatically. The numerical results illustrated in Fig. 4b indicate that by increasing the aspect ratio of the annulus injector, the liquid spray cone angle increases considerably. Also as it has been illustrated in Fig.

4c by further increasing the aspect ratio of the annulus injector, the liquid spray cone angle increases slightly as well.

Numerical results of the hydrodynamic behavior of the liquid fuel sprays resulted from the three annulus nozzles with different aspect ratios and a cylindrical nozzle under the same upstream and downstream boundary conditions reveal that the annulus nozzles affect the hydrodynamic behavior of the liquid fuel spray. Also comparisons between the numerical results among the cases of having just the annulus nozzles with different aspect ratios reveal that by increasing the aspect ratio of the annulus nozzles, the cone angle increases primarily. But by further increasing of the aspect ratio of the annulus nozzle beyond a certain value, the cone angle decreases.

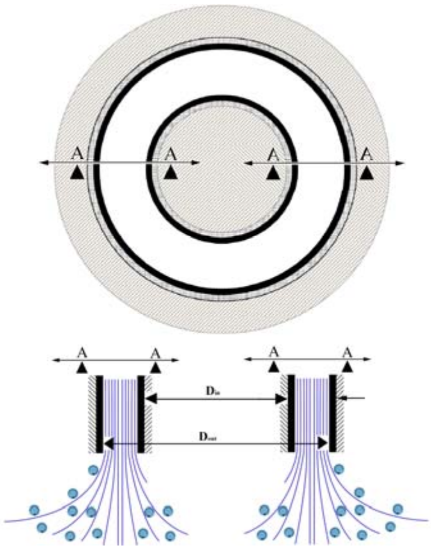


Fig. 5. Increasing the angle of the hollow cone spray by decreasing the thickness of the annulus passage and strengthening of the boundary layers effects.

As it has been illustrated in Fig. 5 schematically, it should be noted that reducing of the thickness of the annulus passage at the exit of a divergent annulus nozzle provides the conditions that the boundary layers on the both inner and outer surfaces of the annulus passage become more effective on the hydrodynamic behavior of the exiting liquid flow from the nozzle. This fact leads to the more outward deflection of the outer surface of the hollow cone liquid fuel spray and more inward deflection of its inner surface.

Figure 6 illustrates variation of the spray penetration length with respect to time in four different aspect ratios. As it is shown in Fig. 6 the spray penetration length in the case of a conventional cylindrical nozzle has the longest magnitude. Figures 6 and 7 also show that the spray penetration length in the cases of 2 and 3 are shorter

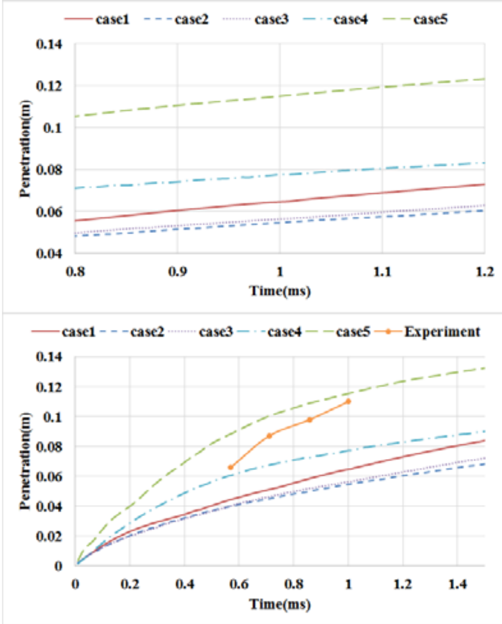


Fig. 6. Variations of the spray penetration length with respect to time.

in comparison with the case of 1 and 4. The physical reasons for this fact that the liquid fuel spray penetration lengths in the different cases of the divergent annulus nozzles are shorter in comparison with the conventional cylindrical nozzle are as follow:

1. Less thickness (Dout-Din=0.02mm) of the annulus passage of the divergent annulus nozzles in comparison with the diameter (d=0.165mm) of the conventional cylindrical nozzle causes production of smaller liquid droplets. These smaller liquid droplets have shorter trajectory path in the gaseous ambient due to their lower inertia forces.

2. Less thickness of the annulus passage at the exit of the divergent annulus nozzle provides the conditions that the boundary layers on both inner and outer surfaces of the annulus passage become significantly effective. This fact decreases velocity of the liquid fuel droplets at the exit of the annulus nozzle's orifice and consequently decreases the liquid fuel spray penetration length.

Figure 6 reveals that by increasing the aspect ratio of the annulus nozzle, the penetration length decreases primarily. Then by further increasing of the aspect ratio of the annulus nozzle beyond a certain value, the penetration length increases.

Figure 7 shows the injected liquid fuel mass with respect to the injection time in the four different cases of the annulus nozzle with different aspect ratios and one conventional cylindrical nozzle. It can be clearly seen in Fig. 7 that injected liquid fuel mass in the case of a conventional cylindrical nozzle is significantly less than the injected liquid fuel mass in the different cases of the annulus nozzle.

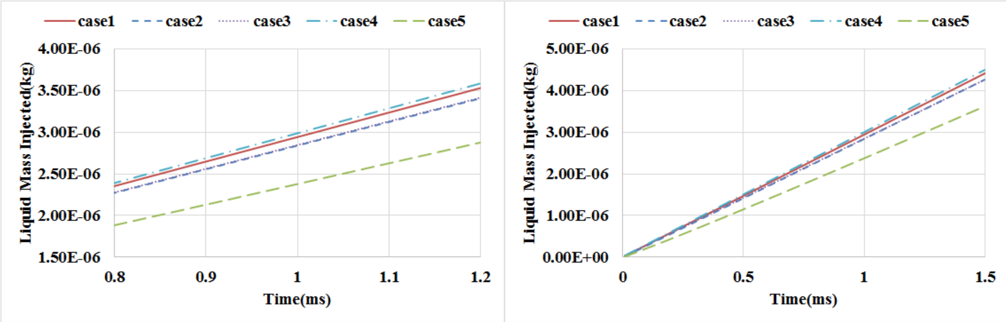


Fig. 7. Variation of the injected liquid fuel mass with respect to the injection time; a) Spanning injection time from 0 to 1.5ms; b) Spanning injection time from 0.8ms to 1.2ms.

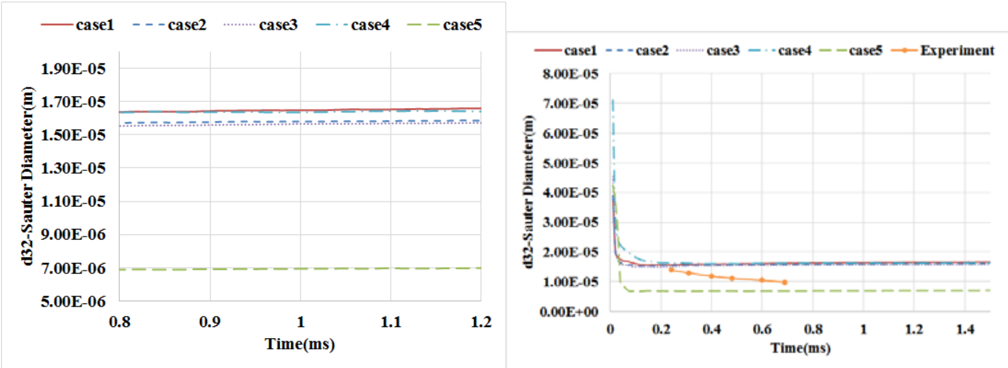


Fig. 8. Variations of the SMD with respect to time for four different cases of the annulus nozzles with different aspect ratios and one traditional cylindrical nozzle.

The amount of the injected liquid fuel mass at the end of the injection time (1.5ms) in the four different cases of the annulus nozzles with the different aspect ratios are approximately the same. This is due to the fact that the magnitudes of D_{in} and D_{out} in the four different cases of the annulus nozzles remain constant.

Figure 8 illustrates variations of the SMD with respect to the injection time for four different cases of the annulus nozzles with different aspect ratios and one conventional cylindrical nozzle.

Despite very slightly variation of the SMD in the cases of the annulus nozzles, it should be noted that distributions of the liquid droplet sizes in the cases of the annulus nozzles are more homogenous than the conventional cylindrical nozzles due to the lack of core of the spray plume which usually consists of the large size droplets.

Figure 8 reveals that by increasing the aspect ratio of the annulus nozzle, the SMD decreases but further increasing of the aspect ratio of the annulus nozzle lead to the increasing of the SMD. Thus Fig. 8 indicates that the proper magnitudes of the aspect ratios which could provide smaller SMD are between the annulus nozzles of the second and third cases.

The physical reasons for this trend of the variations of SMD with respect to the aspect ratio of the annulus nozzle could be from the increasing of the liquid fuel droplets throughout the primary breakup and decreasing of the velocity at the exit of the annulus nozzle. By increasing the aspect ratio of the annulus nozzle, its exit cross section area becomes larger. This fact leads to the larger liquid fuel droplets throughout the primary breakup and to the lower velocity of these liquid fuel droplets. The larger size of the liquid fuel droplets enhances their instability throughout the secondary breakup and consequently lead to smaller magnitudes of the SMD. But on the other hand the low velocity of the liquid fuel droplets at the exit of the annulus nozzle enable the liquid fuel droplets to resist more against the aerodynamic force and keep its stability. Then it can be deduced that the instability of the liquid fuel droplets due to their larger size throughout the secondly breakup from the case 1 to the case 3 is the dominant physical phenomenon which leads to decreasing of the SMD. Also the lower velocity of the liquid fuel droplets at the exit of the annulus nozzle which enables the liquid droplets to resist more against the aerodynamic forces and keep their stability is the dominant physical phenomenon from the case 3 to case 4 which leads to increasing of the SMD.

3.2 Effect of the Divergence Angle of the Annulus Nozzle on the Hydrodynamic Behavior of the Liquid Fuel Spray

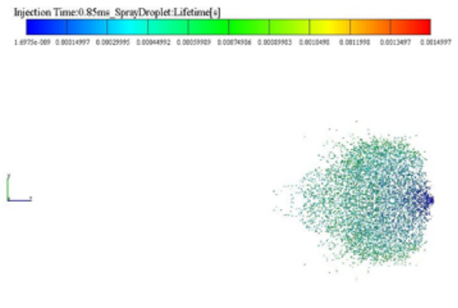
From the first part of the numerical investigations it is found that the annulus nozzles provide better liquid fuel sprays compared to the conventional cylindrical nozzles. It is also found that among the four annulus nozzles with different aspect ratios, the nozzles with the aspect ratios of 2 and 2.5 provide better liquid fuel spray compared to the nozzles with the aspect ratios of 1.5 and 3 Therefor the annulus nozzles with the aspect ratios of 2.5 has been selected for investigating the effect of the divergence angle of the annulus nozzles on the hydrodynamic behavior of the liquid fuel spray.

The divergence angle for the selected annulus nozzle is equal to 10 degrees primarily. Then for obtaining the influence of the divergence angle of the annulus nozzles on the hydrodynamic behavior of the resulted liquid fuel sprays, the second and third magnitudes of the divergence angle of the selected annulus nozzle have been chosen equal to 12° and 8° respectively.

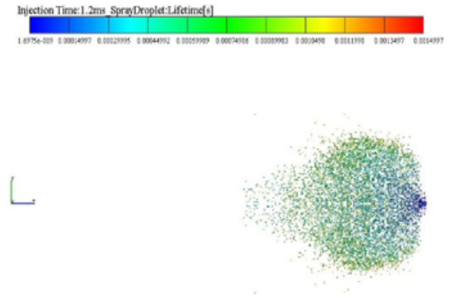
Figure 9 shows the characteristics of a liquid fuel spray's plume resulted from a divergent annulus nozzle with aspect ratio of 0.2 in the case of three different divergence angles of 10°, 12° and 8° respectively.

Although the results shown in Fig. 12a has been illustrated in Fig. 3 previously. But it is included in Fig. 9 for convenience in comparison with the results shown in Figs. 9b and 9c. Figure 9b illustrate the characteristics of the plume of the liquid fuel spray resulted from a divergent annulus nozzle with the aspect ratio of 0.2 and with the divergence angle of 12° in the injection time of 0.85ms and 1.2ms. As it has been shown in Fig. 9b it can be seen that by increasing the divergence angle the spray cone angle increases.

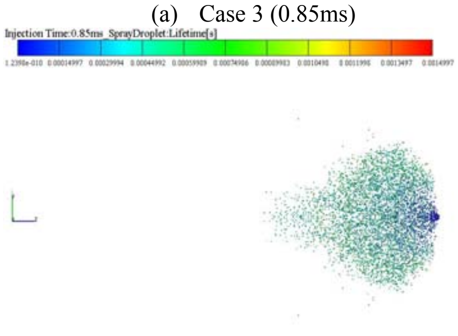
Figure 9c illustrates the characteristics of the plume of the liquid fuel sprays resulted from a divergent annulus nozzle with the aspect ratio of 0.2 and with the divergence angle of 8 in injection times of 0.85ms and 1.2ms. Comparisons between the results of Figs. 9a and 9c reveal that by decreasing the divergence angle of a divergent annulus nozzle with the aspect ratio of 0.2, the cone angle of the liquid fuel spray decreases.



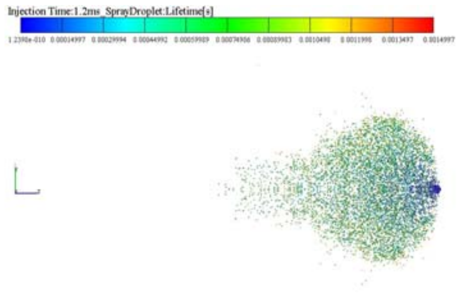
(a) Case 3 (0.85ms)



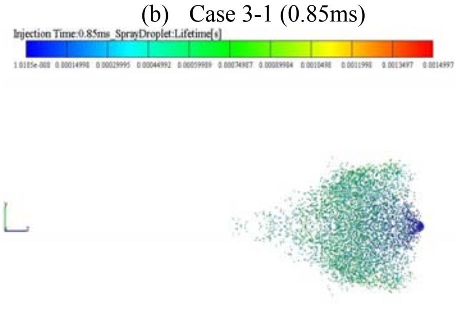
(a) Case 3 (1.2ms)



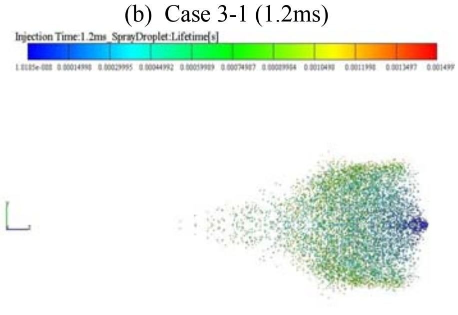
(b) Case 3-1 (0.85ms)



(b) Case 3-1 (1.2ms)



(c) Case 3-2 (0.85ms)



(c) Case 3-2 (1.2ms)

Fig. 9. Characteristics of the plume of the liquid fuel sprays resulted from a divergent annulus nozzle with aspect ratio of 0.2 and with divergence angles of 10°, 12° and 8° in the injection times of 0.85ms and 1.2ms.

Figures 10a and 10b illustrate variations of the penetration lengths of the liquid fuel sprays resulted from the divergent annulus nozzles with aspect ratio of 0.2 for three different convergence angles of 8, 10 and 12 degrees. Figures 13a and 13b in illustrate that the penetration lengths of the liquid fuel sprays resulted from the divergent nozzle with aspect ratio of 0.2 increases considerably when the divergence angle decreases. It can also be seen that by increasing of the divergence angle of the annulus nozzle, the spray penetration length also increases slightly. Therefore it can be deduced that by

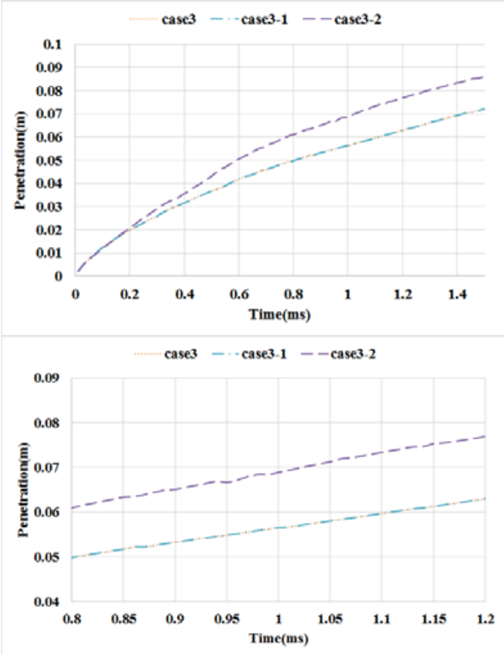


Fig. 10. Variation of the penetration length of a spray resulted from a divergent annulus nozzle with respect to time.

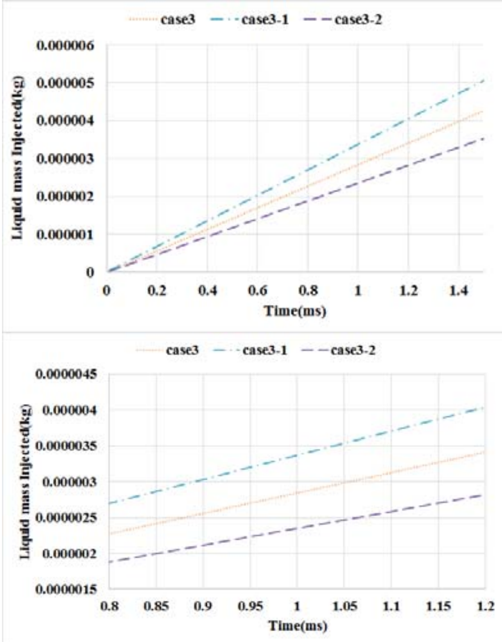


Fig. 11. Variation of the mass flow rate of a spray resulted from a divergent annulus nozzle with respect to time.

increasing the divergence angle of an annulus nozzle from divergence angle 10 by two degrees the penetration length of the resulted liquid fuel sprays increases. This is due to the fact that by increasing the divergence in both cases diameter of the liquid fuel droplets throughout the primary breakup become larger and consequently their inertia forces become more effective. But on the other hand by decreasing the divergence angle by two degrees the penetration length of the resulted liquid fuel sprays increases. This could be from the fact that by decreasing the divergence angle, the cone angle of the resulted liquid fuel spray decreases and the spray's plume becomes smaller. Thus the liquid fuel droplets have more chance to coalescence and make larger droplets with more effective inertia forces.

Figures 11a and 11b illustrate variation of the mass flow rate of the liquid fuel at the exit of the divergent annulus nozzles with the aspect ratio of 0.2 and with the divergent angle of 10°.

Figures 11a and 11b show that by decreasing divergence angle of the annulus nozzles with the aspect ratio of 0.2 and with the divergent angle of 10° by two degrees, the liquid fuel mass flow rate at their exit decrease considerably. These figures also show that by increasing the divergence angle of the above mentioned divergent annulus nozzles by two degrees, the mass flow rate of the liquid fuel at their exit increases considerably. This is due to the fact that by increasing the divergence angle of the annulus nozzle, the pressure drop of the viscous liquid fuel flow through the annulus passage decreases and vice versa decreasing of the divergence angle leads to the increase of pressure drop.

Figures 12a and 12b show variations of the SMD of the liquid fuel sprays resulted from the divergent

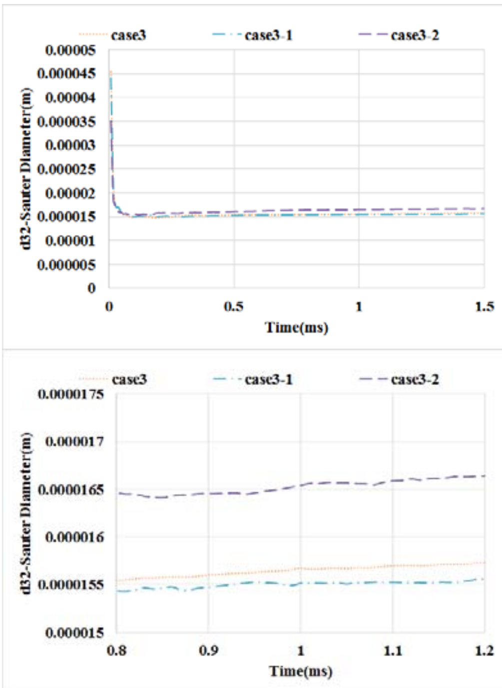


Fig. 12. Variation of the SMD of a spray resulted from a divergent annulus nozzle with respect to time.

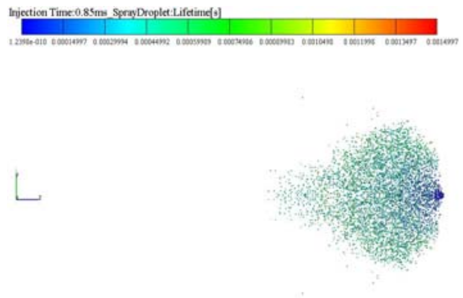
annulus nozzle with the aspect ratio of 0.2 and divergent angle of 10°. Figures 12a and 12b also show variation of the SMD of liquid fuel sprays resulted from the above mentioned divergent annulus nozzle when the divergence angle decreases and increases by two degrees respectively.

Figures 12a and 12b indicate that the SMD of the liquid fuel sprays resulted from the divergent annulus nozzles with the aspect ratio of 0.2 and divergence angle of 10 degrees increases considerably when their divergence angles decrease by two degrees. Whereas in the case of the divergent annulus nozzle with the aspect ratio of 0.2 and divergent angle of 10°, increasing the divergence angle by two degrees decreases the magnitude of the SMD slightly.

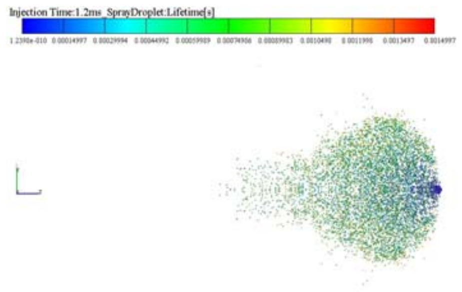
3.3 Numerical Investigations on Increasing of Liquid Fuel Mass Flow Rate

The divergent annulus nozzle with the aspect ratio of 0.2 and the divergence angle of 12° has been selected as the optimum divergent annulus nozzle among the above mentioned annulus nozzles. In this section by keeping all geometrical characteristics of this optimum annulus nozzle constant, the liquid fuel flow rate increases by double fold by increasing of the inner diameter of the annulus passage and increasing of its outer diameter in such a manner that the thickness of the annulus passage remains constant.

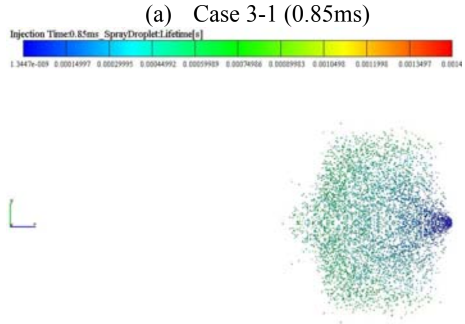
Figures 13a and 13b illustrates the hydrodynamic behavior of the liquid fuel sprays before and after increasing of the mass flow rate of the liquid fuel by double fold respectively at the injection times of 0.85ms and 1.2ms. Figures 13a and 13b clearly indicate that by the dramatic increasing of the liquid fuel mass flow rate, the hydrodynamic behavior of the resulted liquid fuel sprays does not change considerably.



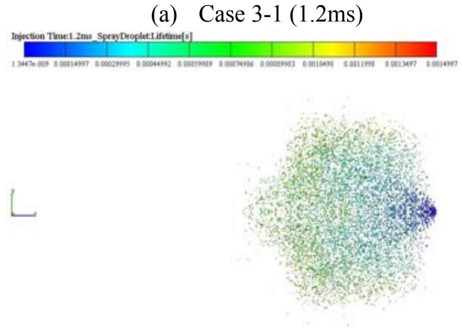
(a) Case 3-1 (0.85ms)



(a) Case 3-1 (1.2ms)



(b) Case 3-1-1 (0.85ms)



(b) Case 3-1-1 (1.2ms)

Fig. 13. Hydrodynamic behavior of the resulted liquid fuel sprays from the nozzle annulus passage in the injection times of 0.85ms and 1.2ms.

Figure 14 illustrates variations of the penetration length of the liquid fuel spray with respect to time before and after increasing of the liquid fuel mass flow rate. Figure 14 shows that by increasing of the liquid fuel mass flow rate by double fold, the penetration length of the liquid fuel spray decreases slightly. This is due to the fact that increasing of liquid fuel mass flow rate occurs by increasing of the inner diameter of the annulus passage by double fold and increasing of its outer diameter in such a manner that the thickness of the annulus nozzle remains constant. Therefore velocity of the liquid fuel at the exit of the annulus passage before and after increasing of liquid fuel flow rate remains constant too and consequently the penetration lengths are the same in both cases.

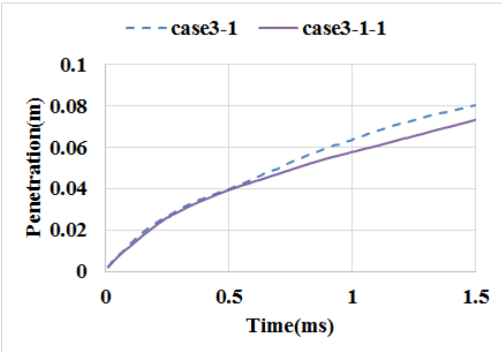


Fig. 14. Variations of the penetration length of a spray resulted from a divergent annulus nozzle with respect to time before and after increasing of the liquid fuel flow rate.

Figure 15 illustrates the variations of the injected liquid fuel with respect to time through the annulus orifice with the aspect ratio of 0.2 and with the divergence angle of 12° in both cases of before and after increasing of the mass flow rate by double fold.

Figure 16 shows the variations of the SMD of the liquid fuel spray with respect to time in the case of having an annulus nozzle with the aspect ratio of 0.2 and with divergence angle of 12° in both cases

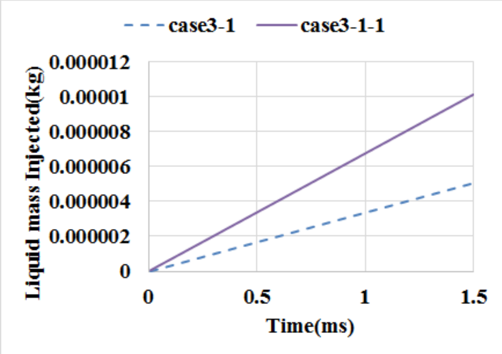


Fig. 15. Variations of the mass flow rate of a spray resulted from a divergent annulus nozzle with respect to time before and after increasing of the liquid fuel flow rate.

of before and after increasing of the liquid fuel mass flow rate. This figure shows that the magnitude of the SMD increases slightly due to the increasing of the mass flow rate by double fold. This is due to the fact that the velocity of the liquid fuel at the exit of the annulus orifice remains constant approximately.

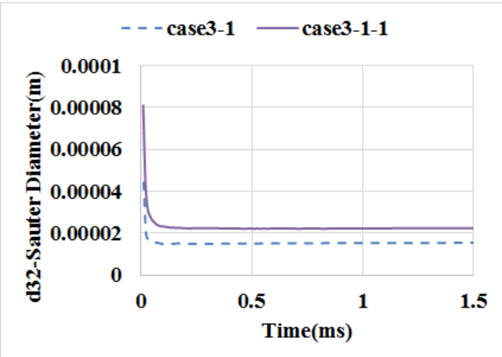


Fig. 16. Variations of the SMD of a spray resulted from a divergent annulus nozzle with respect to time before and after increasing of the liquid fuel flow rate.

4. CONCLUDING REMARKS

In this paper a numerical investigation has been carried out to study the effects of using an annulus injector on the hydrodynamic behavior and characteristics of a liquid fuel spray in internal combustion engines. Numerical results show that by using an annulus injector it is possible to provide a liquid fuel spray plume with a more homogenous distribution of very fine liquid fuel droplets and consequently to improve spray characteristics. Numerical results also reveal that by using an annulus injector it is possible to increase the liquid fuel flow rate without deteriorating the liquid fuel spray hydrodynamic characteristics. It is found that using an annulus injector gives the ability of increasing of the liquid fuel spray cone angle without considerable affecting of the other hydrodynamic characteristics of the liquid fuel spray. Therefore it could be deduced that using an annulus injector could lead to a better combustion in an internal combustion engine and consequently could lead to the reduction of pollutants.

It should be noted that using an annulus injector results in having a hallow cone liquid fuel spray plume and consequently results in the lack of larger liquid fuel droplets which often appears in the core of the traditional cylindrical injector delivered liquid fuel sprays. This numerical investigation shows that using an annulus injector could lead to a liquid fuel spray plume with a shorter penetration length, wider cone angle and more homogenous distribution of very fine liquid fuel droplets compared to the traditional injectors with the cylindrical nozzle hole.

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