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ENHANCEMENT OF SWIRL GENERATION IN DIESEL ENGINE CYLINDER BY USING COMBINATIONS OF TWISTED TAPE AND GUIDE VANES WITH SHROUDED VALVE

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ABSTRACT

Using of shrouded valve creates high swirl ratio inside the engine cylinder. Moreover, using of swirl generation device in the inlet port can improve this swirl ratio. In this paper, both twisted tape and guide vanes devices inserted in the inlet port are used individually for enhancing the generated swirl by the shrouded valve. In addition, the effect of these combinations on the volumetric efficiency and the turbulent kinetic energy (TKE) is studied. A three-dimensional simulation model based on SST k- ω model was used for predicting the air flow characteristics through the inlet port and the engine cylinder in both intake and compression strokes. The results showed that the using of twisted tape and guide vanes with the shrouded valve combinations increases the swirl ratio by 5.2% and 2%, respectively, at the start of injection. They also increase the TKE by 145% and 86.5% but they decrease the volumetric efficiency by about 3%.

Keywords: diesel engine; swirl ratio; shrouded valve; twisted tape; guide vanes

Nomenclature

Bsfc	brake specific fuel consumption, kg/kw.hr
CA	Crank Angle, degree
D_H	hydraulic diameter, m
I	turbulent intensity
IVC	intake valve close
L_{max}	maximum valve lift, m
L_v	valve lift, m
m_i	the mass of air element, kg
Re	Reynolds number
S_R	swirl ratio
SST	shear stress transport
TDC	Top Dead Center
TKE	turbulent kinetic energy

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(v_x, v_y, v_z)	Velocity component in Cartesian coordinate, m/s
(x_i, y_i, z_i)	the coordinates of cylinder center, m
(x_o, y_o, z_o)	the coordinates of the air element center, m
β	the orientation angle, degree
ω_e	the engine angular speed, rad/s
ω_s	the in-cylinder charge angular speed, rad/s

1. Introduction

The flow field characteristics inside the engine cylinder play an effective role in the combustion process in diesel engines. Enhancement of swirl ratio and TKE increases the mixing of the air and the fuel which improves the combustion efficiency and reduces the engine emissions. Many researchers focused their attention on the effect of the inlet valve design on the swirl generation inside the engine cylinder. Raghu and Mehta [1] performed a theoretical analysis for studying the effect of the valve lift, the valve diameter, the seat angle, and the inlet port eccentricity and orientation angle at different engine speeds on swirl generation inside the cylinder. The results demonstrated that these parameters have a great influence on the swirl generation. The inlet valve design parameters (cone angle, seat angle and fillet radius) effect on the inlet flow characteristics and the discharge coefficient through the valve were studied by Maier *et al.*[2], [3]. The results concluded that changes in the valve parameters result in a significant effect on the flow regimes through the valve. Hiregoudar and Shiva [4] used two valve designs for generating swirl in a diesel engine. The first is shrouded valve having two shrouds and the second is a valve having rotating fins. The results demonstrate significant improvements in brake thermal efficiency and engine emissions. Krishna and Mallikarjuna [5] performed an experimental work for studying the effect of using of a shrouded valve at different orientation angles about its axis on the in-cylinder turbulent kinetic energy and tumble ratio. The results showed that the shrouded valve increases the swirl ratio and reduces the tumble ratio.

Other researchers focused their attention on the inlet port design or the inlet ports configurations in the four-valve engines. Kang and Reitz [6] studied experimentally the generation of swirl in a four-valve, engine by using two inlet valves arrangements, alignments valves and inclined valves. The results demonstrated that the aligned valves generated higher swirl and the inclined valves generated higher swirl at high lifts only. They, also, studied the effect of using different configurations of inlet ports with shrouded valves in a heavy duty, four-valves, diesel engine [7]. The inlet ports configurations are; standard, swirl, unti-swirl and tumble ports. The results showed that most of the swirl occurs in the higher part of the cylinder. The influence of using different arrangements of direct and helical inlet ports on swirl generation in diesel engines is studied experimentally by Yufeng et al.[8].The results concluded that direct and helical ports arrangement perpendicular to each other's implemented the highest swirl ratio. A simulation model based on KIVA-3V code is constructed by Ramadan *et al.* [9] for studying the effect the intake system on swirl generation, volumetric efficiency, and TKE. The study was developed using one and two inlet ports with an ordinary and shrouded valve with 180^o shroud angle. The results showed that one inlet port with shrouded valve achieves higher swirl and TKE values and the two inlet ports achieve higher volumetric efficiency. Cantore *et al.* [10] studied numerically the effect of using two configurations of inlet ports on the swirl intensity and breathing capabilities. Steady and unsteady flow simulation models for the intake process are performed, and the results showed that the analysis of steady state is a reasonable tool for determining the inlet port permeability. Four configurations of tangential and helical ports having bypass channel between them were used by Yungjin et al. [11] for studying their effect on the flow coefficient and the swirl ratio variations. In addition, they used Swirl Control Valve (SCV) on the tangential port. The results concluded that the bypass increases the flow coefficient and the SCV increases the swirl ratio. Perini et al. [12] studied the swirl generation in a single cylinder diesel engine experimentally and theoretically. The engine has two inlet ports, one is a tangential and the other is a helical port.

Other attempts tried to increase the swirl ratio by using swirl generation device in the inlet port. Shenghua *et al.* [13] performed an experimental study for testing two new swirl generators on DI diesel engine performance. The first type was formed of several diversions straight blades and the second type was formed of curved blades. They found that the swirl generators reduce the fuel consumption. Yufeng *et al.* [14] performed an experimental work to study the effect of using SCV on air flow inside the engine cylinder. The study was performed on a four-valve engine cylinder and the SCV is fastened on one inlet port while the other is free. The results illustrate that, as the SCV is open, the cylinder flow field is mainly tumbled vortex, and closing the SCV creates a strong swirl vortex in the cylinder through the induction stroke. The SCV is used also by Lee *et al.*[15]. They investigated the effect of its opening angle on the in-cylinder flow using LDV. The results showed that the SCV can achieve a significant variation in the swirl ratio. Kumar and Nagarajan [16] performed an experimental work for studying the influence of the shrouded inlet valve and twisted tape inserted in the inlet port on the flow coefficient, the swirl coefficient and the swirl ratio at different throttle opening and valve lifts. They studied the influence of the shrouded valve and the twisted tape separately. The study is performed on SI engine having direct inlet port by using paddle wheel swirl meter. The results concluded that using of twisted tape or shrouded valve increases the swirl coefficient and swirl ratio on the expense of the flow coefficient. The twisted tape was used also by Srikanth *et al.* [17] in a direct inlet port for studying its effect on the engine performance. They performed experimental work and used 3D CFD code in the simulation model. The results showed that the twisted tape increases the swirl ratio and the TKE. In addition, the engine emissions were reduced and the NO_X increases. A guide vanes inserted in the inlet port was studied theoretically by Saad and Bari [18]. The results showed that guide vanes increase the swirl generation and the turbulence intensity. Sivakumar and Kumar [19] studied numerically the effect of using a vortex generator inserted in the inlet port on the flow characteristics. The results illustrated that using the vortex generator increases the TKE and swirl number which improves the combustion process.

In the previous studies, the twisted tape or the guide vanes or the shrouded valve are used individually for creating air swirl motion. In this study both the twisted tape and the guide vanes are used together with the shrouded valve for creating higher swirl values as follows: (i) using the twisted tape inserted in the inlet port and shrouded inlet valve (ii) using guide vanes inserted in the inlet port and shrouded inlet valve. (ii) studying the effect of the previous combinations on the volumetric efficiency and the turbulent kinetic energy.

2. The engine simulation model

In this study, a four-stroke diesel engine having direct inlet port is chosen as a case study. The engine bore, stroke, compression ratio, and speed are 112mm, 115 mm, 16.4, and 2000 rpm respectively. The intake valve opens 10^o BTDC and closes 42^o ABDC with a maximum valve lift of 12 mm. Shrouded inlet valve having shroud angle of 180^o is used with the direct port. Figure 1 is a schematic diagram illustrates the direct port and the shrouded valve positions with respect to the engine cylinder. The valve orientation angle β in Fig. 1 takes the values of -60, -30, 0, 30 and 60 where the negative values lie below the horizontal axis and the positive values lie above it.

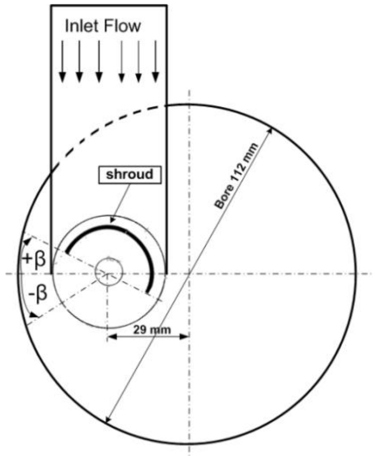

Fig. 1. The inlet port and the shrouded valve positions with respect to the engine cylinder

Two devices are used individually for generating air swirl motion through the inlet port; they are twisted tape and guide vanes. The first device is twisted tape inserted in the inlet port which is illustrated in Fig. 2 a and b. It has a width of 42 mm (equal to the inlet port diameter), a thickness of 2 mm and a twist ratio of 1. The twist ratio is the ratio of the linear distance of the tape for 180^o rotation angle to the width of the tape. Three twisted tapes having rotation angles of 180^o, 360^o and 540^o are used in this study.

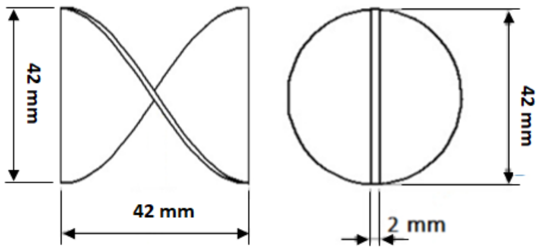

Fig. 2a. The twisted tape geometry and dimensions

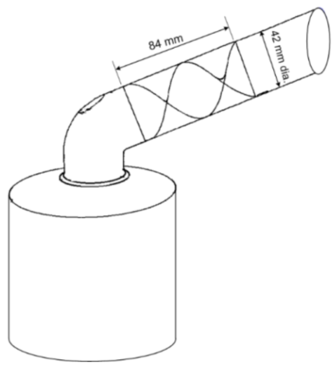

Fig. 2b. Twisted tape inserted in the inlet port

The second device is guide vanes inserted in the inlet port as shown in Fig. 3. The guide vanes are 4 vanes having 90° between each other's with a twist angle of 35°, a length of twice the inlet port diameter (84 mm) and a 2 mm thickness. Different widths of the guide vanes are used. They are; 0.2R, 0.4R, 0.6R, 0.8R, and 1R where R is the inlet port radius (21 mm).

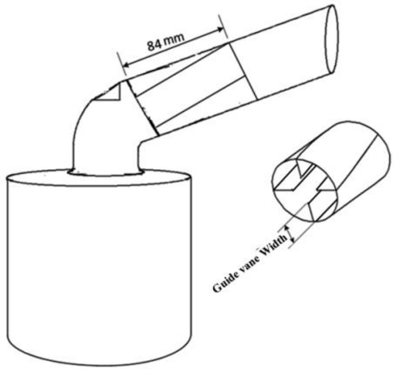

Fig. 3. Guide vanes inserted in the inlet port

The computational domain includes the inlet port with the twisted tape or the guide vanes, the inlet valve and the engine cylinder. The inlet port volume is meshed with stationary mesh type. The valve region volume and the cylinder volume are meshed with deformed mesh type for satisfying the valve and piston motion. The continuity, momentum, and energy equations are solved using SST k-ω simulation model in ANSYS Fluent-14. The pressure and temperature at the inlet port entrance are 101.3 kPa and 300 K. The turbulence intensity at the inlet port entrance is calculated according to the empirical formula of the fully developed flow in the pipe [20].

$$I = 0.16\ (\mathrm{Re}_{D_H})^{-1/8} \quad (1)$$

The swirl ratio is calculated from the velocity field according to the following equation [12], [21].

$$S_R = \frac{\omega_s}{\omega_e} = \frac{\sum_i m_i[(x_i - x_o)v_y - (y_i - y_o)v_x]}{\sum_i m_i[(x_i - x_o)^2 - (y_i - y_o)^2]} \Big/ \frac{2\pi\ N}{60} \quad (2)$$

The suitable mesh size and type are examined where five mesh sizes of 0.3, 0.5, 0.75, 1 and 1.5 mm were selected. The inlet port and the cylinder are divided into three regions; they are the inlet port region, the valve region and the cylinder region. Different mish types are selected for each region. A comparative study is performed with the experimental results of Morse et al. [22] and Bicen at al. [23] in two previous studies [24], [25]. The most suitable mesh size was 0.75 mm and the mesh types are Hex/wedge for the inlet port region, Tet/Hybrid for the valve region and Hex/wedge for the cylinder region. These mesh size and types are selected in the present study.

3. Results and discussion

3.1. Choosing the best orientation angle of the shrouded valve

The shrouded valve has a shroud angle of 180° as shown in Fig. 1. For achieving the maximum swirl ratio, the shrouded valve is oriented around its axis by an orientation angle β. Five values are selected for the angle β, they are -60°, -30°, 0°, 30°, and 60° respectively. The swirl ratio variations through the intake and the compression strokes are illustrated in Fig. 4 for the ordinary valve and the shrouded valve at the different orientation angles. In this figure, the swirl ratio increases for the ordinary valve and the shrouded valve at all valve orientations till about (2/3) the intake stroke due to the increase in the mass flow rate through the inlet valve (Fig. 9) which increases the inlet flow velocity. Then the swirl ratio decreases through the remaining part of the intake stroke due to the decrease in mass flow rate and the inlet velocity. Swirl ratio continues in decreasing through the compression stroke for all valve orientations due to the cylinder wall friction. The using of the ordinary valve generates small values of swirl where the maximum swirl ratio value is 0.97 at 140^o CA through the intake stroke and it decreases to 0.76 at the start of injection because of the direct port and the ordinary valve do not orient the inlet flow to generate swirl. The previous small values of the swirl ratio are generated due to the positioning of the inlet valve left the cylinder center by 29 mm as shown in Fig. 1 where the flow enters the cylinder eccentrically forming weak rotations around the cylinder axis. For the shrouded valve, the swirl ratio increases with orienting the shrouded valve from -60^o to -30^o. It reaches its maximum values at the orientation angle of 0^o with a value of 7.0 at about (2/3) the intake stroke and a value of 4.66 at the start of injection which is about 6 times the produced swirl ratio by the ordinary valve. The swirl ratio decreases with increasing the orientation angle to 30^o and 60^o respectively. Therefore, the shrouded valve with an orientation angle of 0^o will be selected in the following study. For ensuring this result, the swirl ratio variation is calculated at orientation angles of (-5^o and +5^o) and the resulting curves are below the 0^o orientation angle curve by a very low values which enhances the selection of the orientation angle 0^o. Both the twisted tape and the guide vanes will be used with this valve orientation angle for enhancing the swirl inside the engine cylinder.

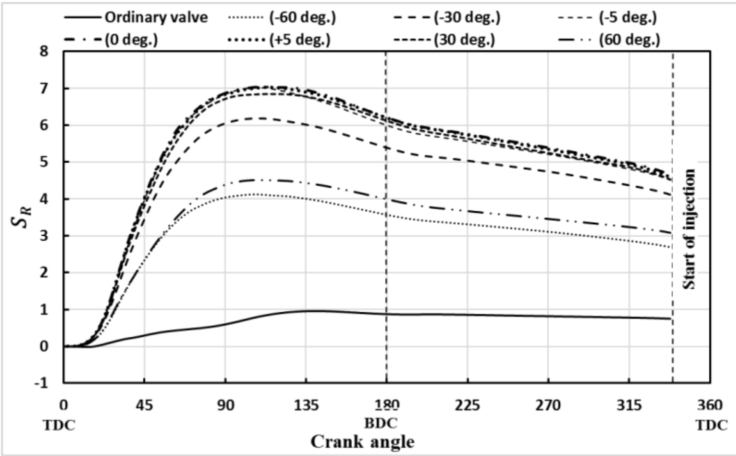

Fig. 4. Swirl ratio variations at different valve orientation angles

3.2. Using of twisted tape only

Figure 5 represents the swirl ratio variations through the intake and the compression strokes for the using of twisted tape inserted in the inlet port. Three twisted tapes having twist ratio of 1 and 180^o, 360^o, and 540^o twist angles are used. Using the twisted tape rotates the inlet flow through the inlet port before reaching the inlet valve. Therefore, the flow enters the cylinder through the valve having a tangential component which produces higher swirl values. Increasing the twisted tape angle from 180^o to 360^o increases the flow rotation around the inlet port axis as the flow rotates complete cycle through the tape length. Hence the swirl ratio increases. Increasing the twisted tape angle from 360^o to 540^o has a very small effect on the flow rotation because of the number of flow rotations per unit length does not increase as the twist ratio is constant. The generated swirl ratio by the twisted tapes of 360^o and 540^o at the start of injection is about 1.85 which is about 2.5 times the generated swirl ratio by the ordinary valve only. Therefore, the 360° twisted tape can be suggested as a suitable tape. It will be used with the shrouded valve for enhancing the swirl ratio in the next section.

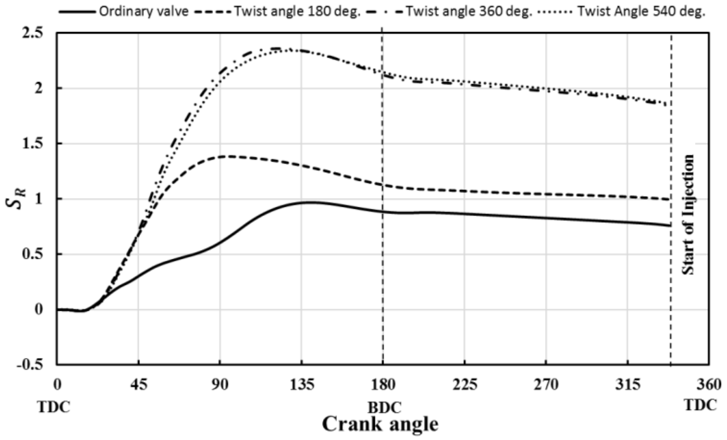

Fig. 5. Swirl ratio variations at different twisted tape angles

3.3. Enhancing the generated swirl by the shrouded valve with the twisted tape

From the previous study, the shrouded valve with an orientation angle of 0° and the twisted tape with a twist angle of 360° achieved the maximum swirl ratios individually. Therefore, this shrouded valve is used for generating the swirl inside the engine cylinder and the 360° twisted tape enhanced it. Figure 6 illustrates the swirl ratio variations through the intake and the compression strokes for the shrouded valve and the shrouded valve with a twisted tape. Using the shroud valve increases the swirl ratio relative to the ordinary valve where it reaches 7 at about 2/3 the intake stroke then it decreases to a value of 4.66 at the start of injection for the same reasons that discussed before. Using of the twisted tape with the shrouded valve increases the swirl ratio to 7.6 at about 2/3 the intake stroke with a percentage increment of 8.6% and it decreases to a value of 4.9 at the start of injection with a percentage increment of 5.2% relative to the shrouded valve. Therefore, the twisted tape has a considerable effect on the swirl generation through the engine cylinder.

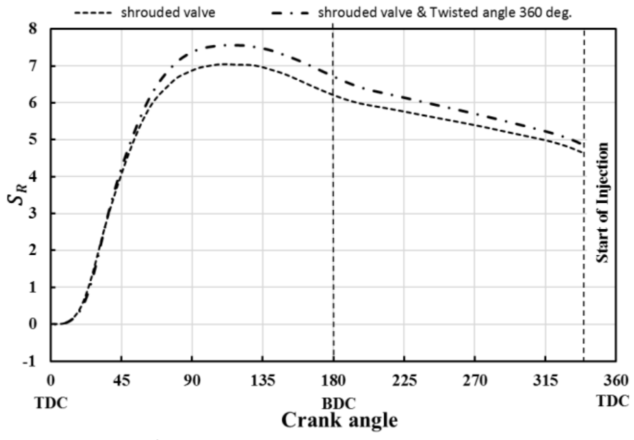

Fig. 6. Swirl ratio variations for the shrouded valve and the shrouded valve with twisted tape.

3.4. Using of guide vanes only

Figure 7 illustrates the swirl ratio variations through the intake and the compression strokes for the using different widths of guide vanes inserted in the inlet port. They are; 0.2R, 0.4R, 0.6R, 0.8R, and 1R, respectively. The swirl ratio increases with the use of the guide vanes with respect to the using of the direct port only at all guide vanes widths as the guide vanes surface twists the flow streamlines through the inlet port around the port axis. At the same time, the guide vanes produce flow resistance due to the surface friction between the air flow and the vanes surfaces. The flow resistance could be an acceptable reason for reducing the inlet mass flow rate (Fig. 9) and hence it reduces the generated swirl inside the cylinder. Due to these two opposite effects of the guide vanes, different widths are used to choose the best width. The swirl ratio increases with the increase of the guide vanes width up to 0.6R as the streamlines twisting effect is higher than the flow resistance effect. Increasing the guide vanes width to 0.8R and 1.0R reduces the swirl ratio as the flow resistance effect is higher than the stream twisting effect. Guide vanes of 0.6R width produce the maximum swirl ratio with a value of 1.3 at the start of injection which is approximately 1.7 times the using of direct port only with the ordinary valve. For insuring this width value, a half step is used before and after it, they are 0.5R and 0.7R widths. The resulting swirl ratio curves are below the generated curve by the 0.6R guide vanes width. Therefore, the guide vanes with 0.6R width will be used with the shrouded valve for enhancing the swirl inside the engine cylinder in the next section.

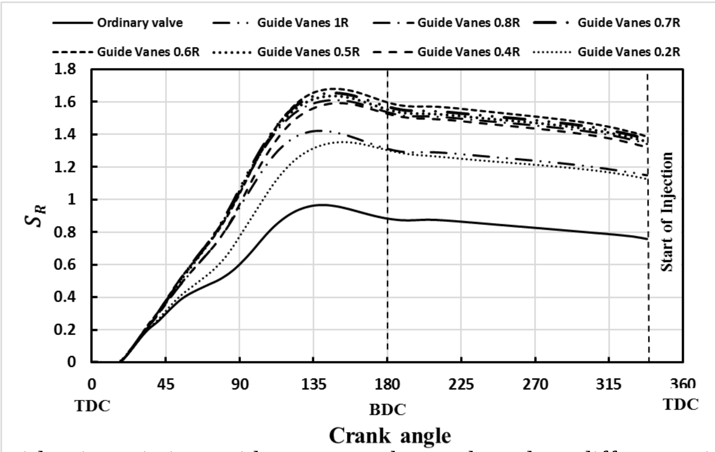

Fig. 7. The swirl ratio variations with respect to the crank angle at different guide vanes widths.

3.5. Enhancing the generated swirl by the shrouded valve with guide vanes

Figure 8 illustrates the swirl ratio variations through the intake and the compression strokes for the using of a shrouded valve and shrouded valve with the guide vanes. The shrouded valve has an orientation angle of 0^o and the guide vanes have a width of 0.6R as they produce the maximum swirl ratio individually. Using the guide vanes with the shrouded valve has a small effect on the increase of the swirl ratio as its value is 7.21 at about (2/3) the intake stroke with a percentage increment of 3% and 4.75 at the start of injection with a percentage increment of 2% relative to the using of the shrouded valve only.

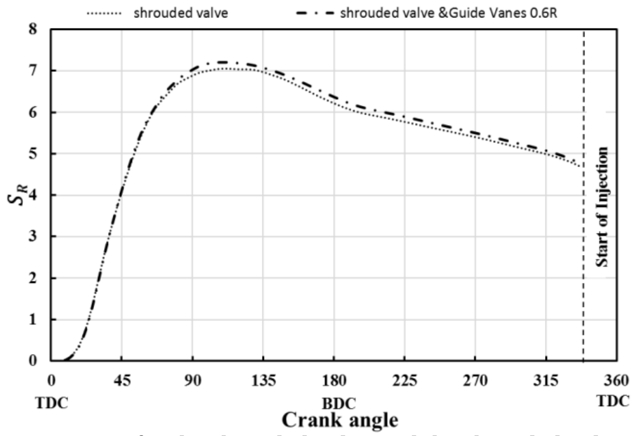

Fig. 8. Swirl ratio variations for the shrouded valve and the shrouded valve with the guide vanes

4. The effect of the twisted tape and the guide vanes on the volumetric efficiency

The twisted tape, the guide vanes, and the shrouded valve produce flow resistance as they represent obstacles for the flow streamlines besides their friction effect on the inlet flow. Therefore, the mass flow through the inlet valve is smaller than that of the direct port only with the ordinary valve. Figure 9 illustrates the mass flow rate through the inlet valve for the direct inlet port only with the ordinary valve besides the inlet port with twisted tape and guide vanes with a shrouded valve. The mass flow rate of the ordinary valve case is more than that of the other two cases. Integrating the mass flow rate profiles with respect to time and calculating the volumetric efficiency for the three cases results in the volumetric efficiency of the ordinary valve case, the twisted tape case and the guide vanes case are 96.5%, 93.2%, and 93.4%, respectively.

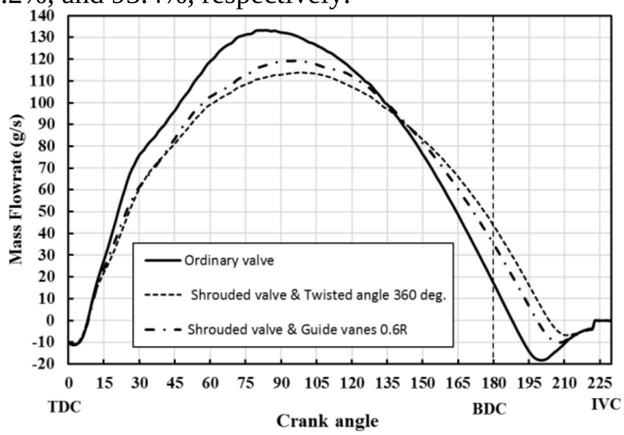

Fig. 9. Mass flow rate variations through the intake and the compression strokes.

5. The Effect of the twisted tape and the guide vanes on the TKE

The TKE is the mean value of the kinetic energy for unit mass corporated with eddies in the turbulent flow [26]. It helps in the breakdown of the fuel molecules and hence it improves the combustion process and increases the combustion efficiency. Figure 10 shows that the TKE increases gradually through the first half of the intake stroke due to the increase of the inlet flow velocity which increases the turbulence intensity inside the cylinder and hence the TKE. Then it decreases in the second half of the intake stroke due to the decrease in the inlet flow velocity. It continues decreasing through the compression stroke due to the cylinder wall friction and the energy dissipation rate in the in-cylinder charge. The TKE values at the start of injection for the ordinary valve case, twisted tape case and guide vanes case are 17.56 m^2/s^2, 42.93 m^2/s^2 and 32.73 m^2/s^2 respectively. The percentage increments of the twisted tape case and the guide vanes case are 145% and 86.5% respectively relative to the ordinary valve case.

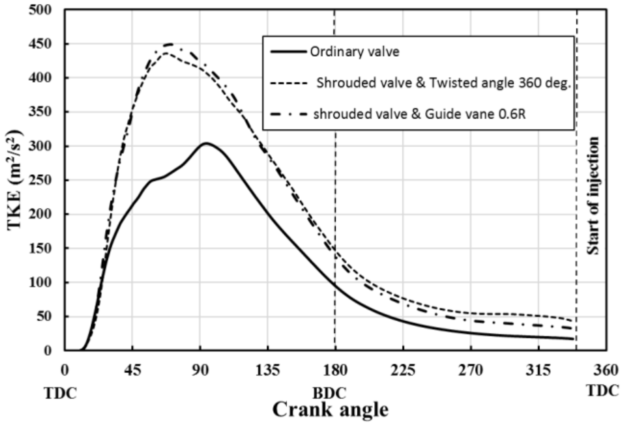

Fig. 10. The TKE variations through the intake and the compression strokes.

6. Conclusion

A theoretical study is performed on enhancing the generated swirl by the shrouded valve with twisted tape and guide vanes inserted in the inlet port. The study is performed using the SST k-ω simulation model in ANSYS Fluent-14. A shrouded valve having shroud angle of 180° at different orientation angles is used and the best orientation angle is selected. Three twisted tapes having twist angles of 180°, 360° and 540° are used for choosing the best twist angle. Five guide vanes having widths of 0.2R, 0.4R, 0.6R, 0.8R and 1 R are used for choosing the best width value. The shrouded valve at the best orientation angle is selected for generating swirl inside the cylinder and both the twisted tape and the guide vanes, at their best conditions, are used individually for enhancing the generated swirl by the shrouded valve. The effect of the twisted tape and the guide vanes combinations with the shrouded valve on the volumetric efficiency and the turbulent kinetic energy is studied also. The output results can be concluded in the following points:

1- Using of the shrouded valve generates high swirl ratio 4.66 at the start of injection.
2- Using of the twisted tape with shrouded valve enhances the swirl ratio to 4.9 with a considerable percentage increment of 5.2% at the start of injection relative to the using of the shrouded valve only.
3- Using of the guide vanes with shrouded valve enhances the swirl ratio to 4.75 with a small percentage increment of 2% at the start of injection relative to the using of the shrouded valve only.
4- Using of the twisted tape and the guide vanes combinations with the shrouded valve reduces the volumetric efficiency by about 3% relative to the using of the ordinary valve only.
5- The twisted tape and the guide vanes combination with the shrouded valve increase the TKE at the start of injection by 145% and 86.5% respectively.

6- The using of a twisted tape is better than the using of the guide vanes as it produces more enhancements for the swirl ratio and the TKE with the same reduction effect on the volumetric efficiency.

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تعزيز توليد الدوامة في أسطوانة محرك الديزل باستخدام تركيبات من الشريط الملتوي وريش التوجيه مع صمام ذو سياج

الملخص العربى:

إن استخدام الصمام ذو السياج يؤدي إلى ارتفاع نسبة الدوامة داخل أسطوانة المحرك. وعلاوة على ذلك فإن استخدام أحد أجهزة توليد الدوامة داخل قناة السحب يمكن أن يزيد من نسبة الدوامة. في هذا البحث تم استخدام كل من الشريط الملتوي وريش التوجيه في مدخل قناة السحب ,كلٌ على حده, لتعزيز الدوامة المتولدة من قِبَل الصمام ذوالسياج. بالإضافة إلى ذلك، تم دراسة تأثير هذه التركيبات على الكفاءة الحجمية والطاقة الحركية المضطربة (TKE). تم استخدام نموذج محاكاة ثلاثي الأبعاد يعتمد على نموذج SST k- ω للتنبؤ بخصائص تدفق الهواء من خلال قناة السحب وأسطوانة المحرك في كل من مشواري السحب والضغط. وأظهرت النتائج أن استخدام الشريط الملتوي وريش التوجيه مع الصمام ذو السياج يزيد من نسبة الدوامة بنسبة 5.2٪ و 2٪ على التوالي، عند بداية الحقن. كما أنها تزيد من الطاقة الحركية المضطربة بنسبة 145٪ و 86.5٪ ولكنها تقلل من الكفاءة الحجمية بنحو 3٪.