KINEMATIC ANALYSIS OF PISTON MECHANISM IN VALVELESS INTERNAL COMBUSTION ENGINE WITH MORE COMPLETE EXPANSION

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INTRODUCTION

Today, there is a very large number of successful construction of internal combustion engines, which are applied to various fields of science and technology. In some areas IC engines are so dominant without concurrence of other types of engines. This fact suggest that today's internal combustion engines are at a high technical level. However, construction of piston stroke internal combustion engines that are now used is based on inefficient thermodynamic and mechanical concept. It can be said that the main characteristics of today's engine is very small amount of work in relation to used fuel, in other words, today's engines have a very low coefficient of efficiency. Realistically speaking *Otto* engines today use about 25% of input energy, while *diesel* construction about 30% (in some cases can be expected a little more). Approximately 35% of the *Otto* engine and 30% of heat in the diesel engines goes through exhaust and around 33% goes for cooling the engine in both versions, other 7% is attributed to friction and radiation [1]. For illustration can be taken into account combustion of one liter of diesel in the classical combustion engines. Combustion of this amount of fuel frees approximately 39 MJ of power, the engine output shaft is generated only around 13 MJ, while with other 26 MJ engine heated environment.

Considering the present development trends, trends for more efficient use of fuel resources, the problem of global warming and other environmental factors, development of internal combustion engines will certainly move towards the reduction of fuel consumption[2,3]. In this paper one of the possible ways of reducing thermodynamic losses in the IC engine is shown.

KINEMATIC OF CONVENTIONAL IC ENGINE

Movement of the piston in conventional IC engines is based on relatively simple kinematic [4]. Fig 1. shows the kinematics of a crankshaft drive with crossing, in which the longitudinal crankshaft axel does not intersect with the longitudinal cylinder axel, but rather is displaced by the lenght e.

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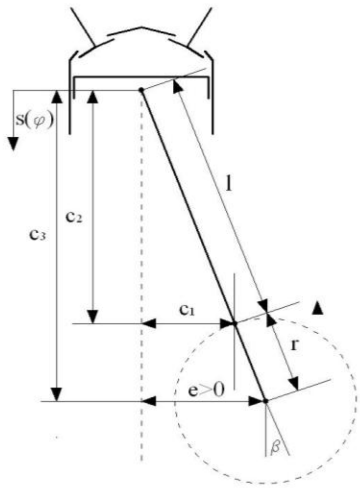

Figure 1: *Kinematic scheme of conventional IC engines*

For the piston path $s(\varphi)$, it follows from Fig 1.

$$s(\varphi) = c_3 - c_2 - r\cos(\varphi - \beta) \tag{1}$$

from which with

$$\sin\beta = \frac{e}{r+l} \quad \text{and} \quad \beta = \arcsin\left(\frac{e}{r+l}\right)\text{, respectively}$$
$$\begin{aligned} c_1 &= e - r\sin(\beta - \varphi) \\ c_2 &= \sqrt{l^2 - c_1^2} \\ c_3 &= \sqrt{(r+l)^2 - e^2} \end{aligned} \tag{2}$$

Finally

$$s(\varphi) = \sqrt{(r+l)^2 - e^2} - \sqrt{l^2 - [e + r\sin(\varphi - \beta)]^2} - r\cos(\varphi - \beta) \tag{3}$$

results. The derivative provides for the piston speed the relation

$$\frac{ds}{d\varphi} = r\sin(\varphi - \beta) + \frac{r[e + r\sin(\varphi - \beta)]\cos(\varphi - \beta)}{\sqrt{l^2 - [e + r\sin(\varphi - \beta)^2]}} \tag{4}$$
.

With the definition of the cylinder volume

$$V(\varphi) = V_C + D^2 \frac{\pi}{4} s(\varphi) \tag{5}$$

follows for the alteration of cylinder volume

$$\frac{dV}{d\varphi} = D^2 \frac{\pi}{4} \frac{ds}{d\varphi} \tag{6}$$

With the eccentric rod relation $\lambda = r/l$, it follows for the limiting case *e=0.*

$$s(\varphi) = r\left\{[1 - \cos(\varphi)] + \frac{1}{\lambda_k}\left[1 - \sqrt{1 - \lambda_k^2 \sin^2(\varphi)}\right]\right\} \tag{7}$$

and

$$\frac{ds}{d\varphi} = r\left[\sin(\varphi) + \frac{\lambda_k}{2} \frac{\sin(2\varphi)}{\sqrt{1 - \lambda_k^2 \sin^2(\varphi)}}\right] \tag{8}$$

Through this kinematics, movement of the piston is very limited. Conventional piston movement in Otto engine cause changes of working fluid described in Fig 2.

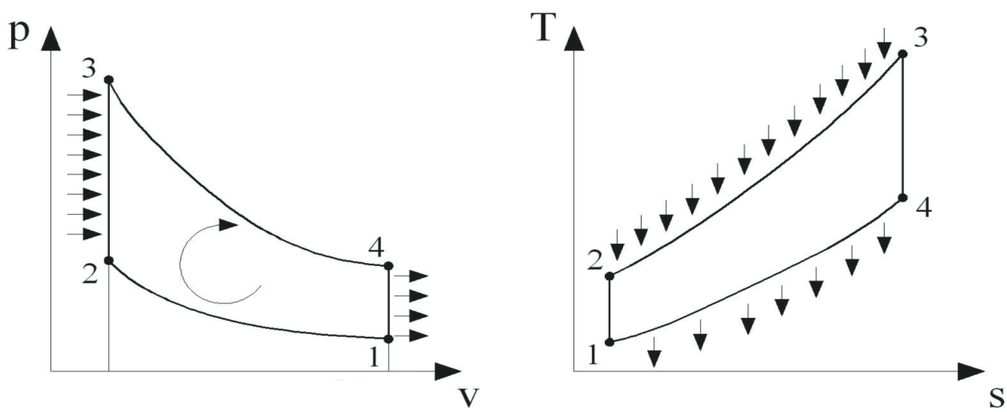

Figure 2: *PV and TS diagram of conventional IC engines*

As in Fig. 2, the compression 1-2 process is isentropic; the heat addition 2-3, an isochoric process; the expansion 3-4, an isentropic process; and the heat rejection 4-1, an isochoric process. For the heat addition (2-3) and heat rejection (4 -5) stages, respectively, it is assumed that heating occurs from state 2 to state 3 and cooling ensues from state 4 to state [5].

Miller cycle

The Miller cycle, named after its inventor R.H. Miller, has an expansion ratio exceeding its compression ratio. The Miller cycle, shown in Fig. 3, is a modern modification of the Atkinson cycle (i.e., a complete expansion cycle). In the Miller cycle, the intake valve is left open longer than it would be in an Otto cycle engine. In effect, the compression stroke is two discrete cycles: the initial portion when the intake valve is open and final portion when the intake valve is closed. TS and PV diagrma of Miller cycle are presented in Fig. 3.

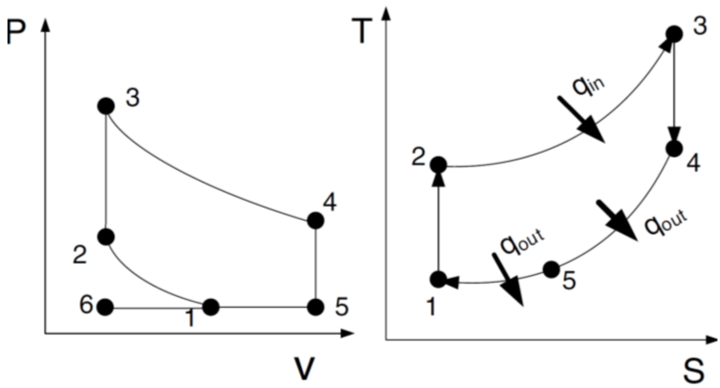

Figure 3: *Pv and TS diagram of Miller cycle IC engine*

It is obvious that is very important for thermodynamic efficiency that temperature at the end of expansion be as small as possible. This lower temperature will give a larger surface of TS diagram, larger surface of TS diagram means greater efficiency. As can be seen from PV diagram, in Miller cycle compression and expansion stroke are not same length geometrically speaking. With conventional piston mechanism is very difficult to achieve this motion. In new internal combustion engine this complex movement can be perform much easier. It is very important for modern IC engines to work on such cycle, because this thermodynamic cycle have many advatanges over standard Otto cycle, one of them are:

- Less fuel consumption.
- Less heating of the environment.
- Less pollution

DESCRIPTION OF ENGINE

In this mechanism movement of piston is different than in conventional IC engine. The main idea can be described with kinematic scheme in Fig. 4.

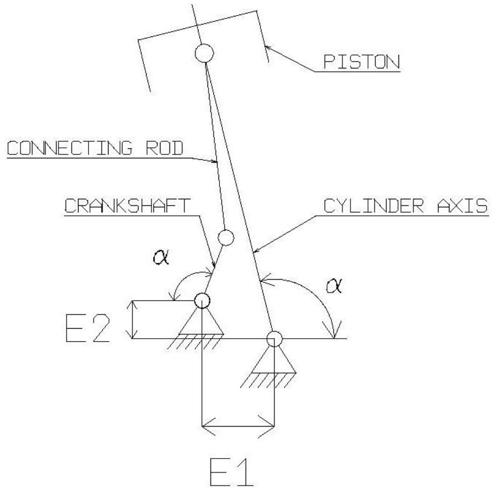

Figure 4**:** *Kinematic scheme of new piston mechanism*

As seen in Fig. 4, in this case to the conventional piston mechanism scheme is added one more movement (rotation) of cylinders around axis at exactly defined position. Precisely defined position of the crankshaft and movable cylinders is very important, because these values define more complete expansion of working fluid and full discharge combustion chamber of the residual products of combustion, impact of these values on more complete expansion are described in [6].

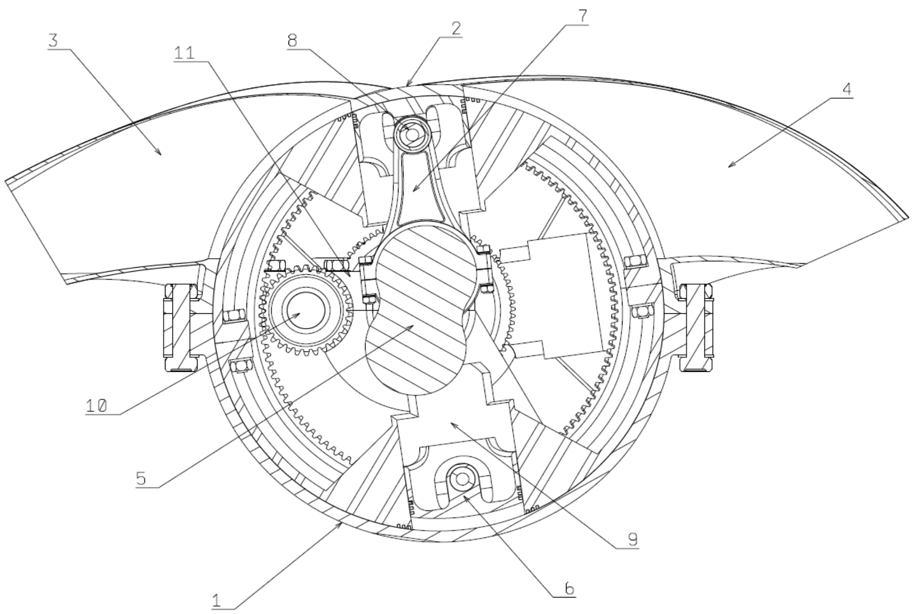

Figure 5: *Cross-section of new IC engine*

Basic parts of engine are shown in Fig 5. The engine consist of the lower part of engine block (1) and the upper part of the engine block (2), movable cylinders - rotors (9), in which are placed pistons (6), connected to the crankshaft (5), through the piston rod (7) and piston pin (8). With (3) and (4) are presented intake and inlet manifold respectively, and with (10) and (11) are described gear mechanism. Pistons are placed radially to the crankshaft, whereby the rotation axes of crankshaft located at precisely defined position The Miller cycle, named after its inventor R.H. Miller, has an expansion ratio exceeding its compression ratio. The Miller cycle, shown in Fig. 1, is a modern modification of the Atkinson cycle (i.e., a complete expansion cycle). In the Miller cycle, the intake valve is left open longer than it would be in an Otto cycle engine. In effect, the compression stroke is two discrete cycles: the initial portion when the intake valve is open and final portion when the intake valve is closed. In new valveless IC engine with more complete expansion of working fluid Miller cycle is achieved in a different way.

KINEMATIC OF VALVELESS IC ENGINE WITH MORE COMPLETE EXPANSION

Projections of the kinematic schemes from the Fig. 4 may be expressed through the two axes.

Projection of the x-axis s is given in next Eg (9)

$$s \cdot \sin(\alpha) = L \cdot \sin(\beta) + r \cdot \sin(-\alpha) + l \cdot \sin(\gamma)$$

$$\gamma = a\sin\left(\frac{s \cdot \sin(\alpha) - L \cdot \sin(\beta) + r \cdot \sin(\alpha)}{l}\right) \tag{9}$$

and for y-axis Eg (10):

$$s \cdot \cos(\alpha) = L \cdot \cos(\beta) + r \cdot \cos(-\alpha) + l \cdot \cos(\gamma)$$

$$\gamma = \pi - a\cos\left(\frac{(-s) \cdot \cos(\alpha) + L \cdot \cos(\beta) - r \cdot \sin(\alpha)}{l}\right) \tag{10}$$

Values of speed, acceleration and position will depend on the selected kinematics parameters. In this case the tendency was the construction of the IC engine that can run the usual car. In accordance with the use of engine in the field of passenger motor vehicles the following parameters are selected.

Kinematics parameters of piston mechanism:

- r =30 [mm] - crankshaft radius,
- L=115 [mm] - connecting rod lenght,

- $\lambda_k = \dfrac{r}{L} = \dfrac{30}{115} = 0.26$ - rod relation,
- $\omega_k = \dfrac{\pi \cdot n}{30} = \dfrac{3.14 \cdot 3000}{30} = 314\left[s^{-1}\right]$- angular speed of crankshaft,
- $\omega_c = -\dfrac{\pi \cdot 3000}{30} = -\dfrac{3.14 \cdot 3000}{30} = -314\left[s^{-1}\right]$ - angular speed of rotor,
- $\omega_k = -\omega_c$,
- $E_1 = 13{,}8[mm]$,
  $E_2 = 2{,}3[mm]$.

Simple kinematic analysis shows that the lenght of certain strokes are:

- $s_u = 49.3[mm]$ - intake stroke
- $s_s = 44.5[mm]$ - compression stroke
- $s_{\check{s}} = 72.1[mm]$ - expansion stroke
- $s_i = 76.9[mm]$- exhaust stroke

Piston distance in function of the angle of crankshaft are shown in Table 1.

Table 1: *Piston distance from rotation axis of rotor*

angle *[^{o}]*	*distance* [mm]	*angle* *[^{o}]*	*distance* [mm]	*angle* *[^{o}]*	*distance* [mm]	*angle* *[^{o}]*	*distance* [mm]
0	147.924	90	99.4357	180	137.59	270	72.1387
4.5	147.421	94.5	100.545	184.5	134.059	274.5	73.4323
9	146.027	99	102.169	189	129.842	279	75.2788
13.5	143.826	103.5	104.289	193.5	125.068	283.5	77.6872
18	140.933	108	106.873	198	119.886	288	80.6633
22.5	137.479	112.5	109.877	202.5	114.457	292.5	84.2051
27	133.61	117	113.244	207	108.94	297	88.2981
31.5	129.478	121.5	116.898	211.5	103.488	301.5	92.9091
36	125.231	126	120.745	216	98.2372	306	97.9817
40.5	121.01	130.5	124.673	220.5	93.3021	310.5	103.433
45	116.94	135	128.557	225	88.7718	315	109.151
49.5	113.127	139.5	132.259	229.5	84.7104	319.5	114.999
54	109.661	144	135.636	234	81.1595	324	120.821
58.5	106.607	148.5	138.549	238.5	78.1423	328.5	126.446

angle [º]	*distance* [mm]	*angle [º]*	*distance* [mm]	*angle [º]*	*distance* [mm]	*angle [º]*	*distance* [mm]
63	104.017	153	140.863	243	75.6682	333	131.703
67.5	101.924	157.5	142.465	247.5	73.7383	337.5	136.428
72	100.352	162	143.262	252	72.349	342	140.474
76.5	99.3133	166.5	143.187	256.5	71.4958	346.5	143.719
81	98.8144	171	142.209	261	71.1758	351	146.073
85.5	98.8563	175.5	140.331	265.5	71.3889	355.5	147.481

Values from the Table 1 can be described through diagram, such a diagram is shown in Fig 10. From the diagram it can be observed that all four strokes have different lenghts. The values of the length of strokes can be easily changed depending on desired ratio of compression and expansion ratio. In this case, the tendecy was to accomplish the compression ratio of approximateley 10.3 , and expansion ratio of approximateley 15.

It is interesting to make an analysis of piston movement through space, it can be easily done by solving Eq (9) and Eq (10) with respect to values of kinematics parameters of piston mechanism. In this case movement of the piston is not a linear, because in this engine kinematics of piston mechanism forces the piston to move over curve. Piston is moving on very complex curve. This curve can be described by the following Fig. 6. As can be seen from this diagram this curve is very similar to ellipse. The parameters of this curve depends on the value of the following factors: crankshaft radius , connecting rod lenght, rod relation and also of values of eccentric parameters E_1 and E_2. It is clear that with these parameters it is easy to achieved very large number of different types of curves, in other words different type of piston motion law. In this type of kinematics chain small changes of values are reflected in wide variations. For example, angular velocity must be of the same intensity for the movable cylinders and crankshaft, but opposite directions. Also the gear ratio must be respected, only in this case engine can reach the proper cycle operation.

By changing described values, engine can achieve much higher expansion ratio than standard conventional IC engine. This is very important because with longer expansion stroke working fluid can reach much lower temperature at the end of expansion According to Fig. 3 it is clear that with the reduction of T_4 (temperature at the end of expansion) cycle achieves a greater surface of TS diagram, larger surface of TS diagram mens greater efficiency**.**

After analyzing the trajectories of the piston, it is necessary to perform the analysis of velocity and acceleration. Compared to traditional engine, in this concept velocity and acceleration have more complex components. Fig. 5 shows IC engine with kinematic scheme from Fig. 4, as can be seen from both pictures piston will be forced to complex movement. This complex movement will consist of two components. First one is the result of movement of piston through the cylinder, while the other component is velocity due rotation of cylinders. These two values of velocities are very different in terms of the intensity and law changes. Vector addition of these components gives absolute velocity of piston. This design of IC engine allows development of all four cycle for one revolution of crankshaft. For these reasons, this engine can achieve the same number of working cycles as conventional IC engine with the half angular velocity of crankshaft. Therefor in the further analysis was used angular velocity of crankshaft of 3000 rpm, because this values of angular speed corresponding to 6000 rpm in conventional IC engine, which is near the maximum for standard engines.

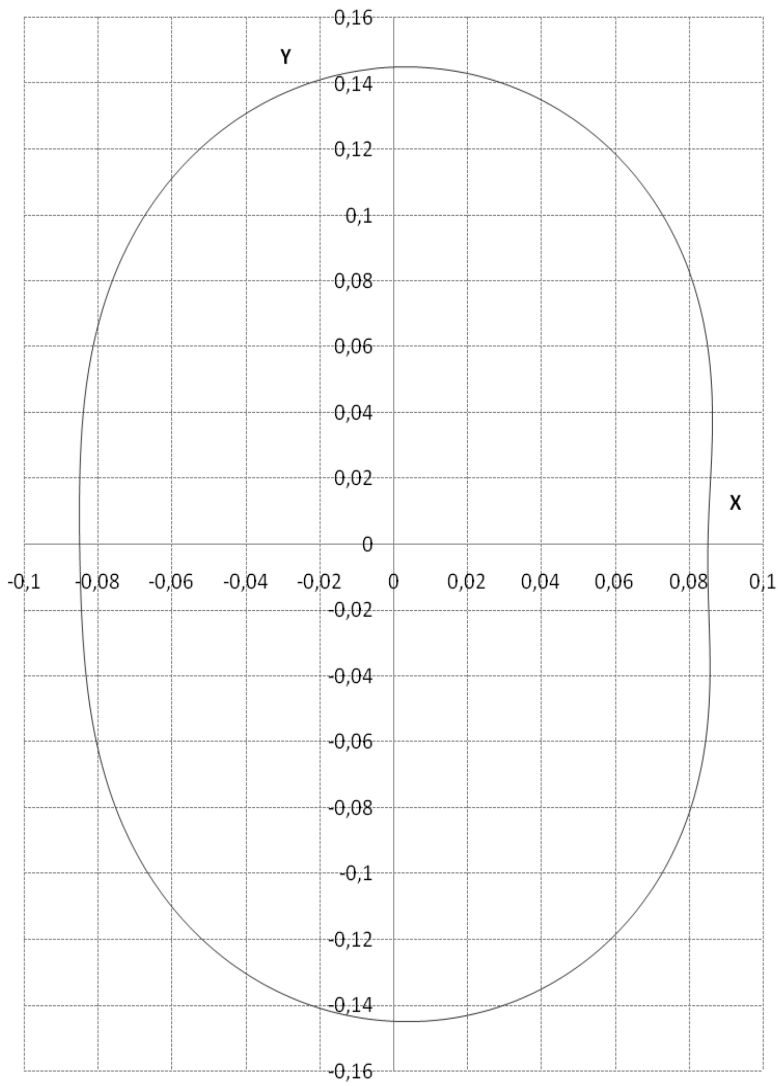

Figure 6: *Piston path in new IC engine*

The graphic in Fig. 7 represents the change in velocity of piston through the cylinder. As can be see from the same Fig. 7 law of motion is very similiar to standard motion law of piston in standard engine. However, noted is that the amplitude for some strokes are not the same, which is direct consequence of non-conventional kinematics, in other words the tendency to make a longer expansion than compression stroke. In the next diagram in Fig. 8

change of absolute velocity of piston is shown. Here can be observed the greatest differences between conventional and non-conventional kinematics. From the Fig. 8 it can be noticed that the velocity of piston is never equal to zero, in other words, piston in this engine never stops, also velocity is nearly constant in a large part of movement. As is well known in standard IC engine pistons need four times per whole cycle to stop. Finally, Fig. 9 represents the relative acceleration of the piston. This results is especially interesting, because he shows how the engine construction achieves more complete expansion. As is well know shape of the acceleration curve depends on the kinematics factor, i.e. the number of maximum values of acceleration function depends of ratio R/L. In this mechanism for the first part of movement acceleration curve have one maximum values and for the second part have two maximum, this can be concluded by observing Fig. 9. This feature achieve more complete expansion.

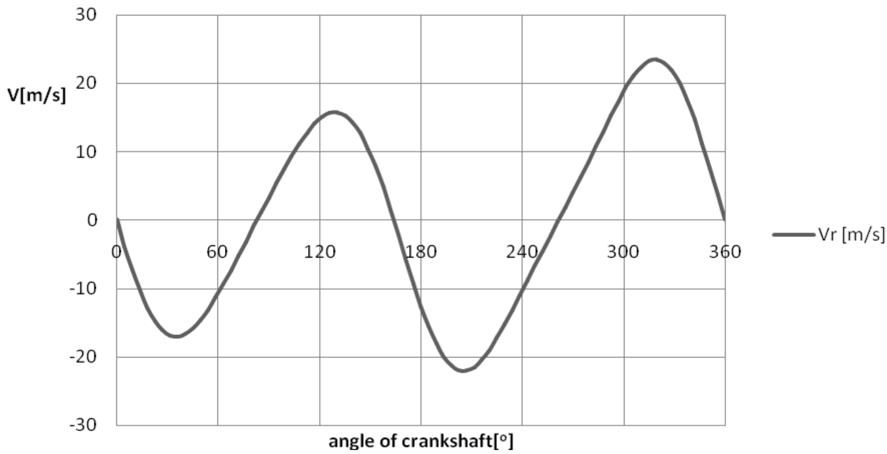

Figure 7**:** *The relative velocity of piston at 3000 rpm (velocity of piston through the cylinder)*

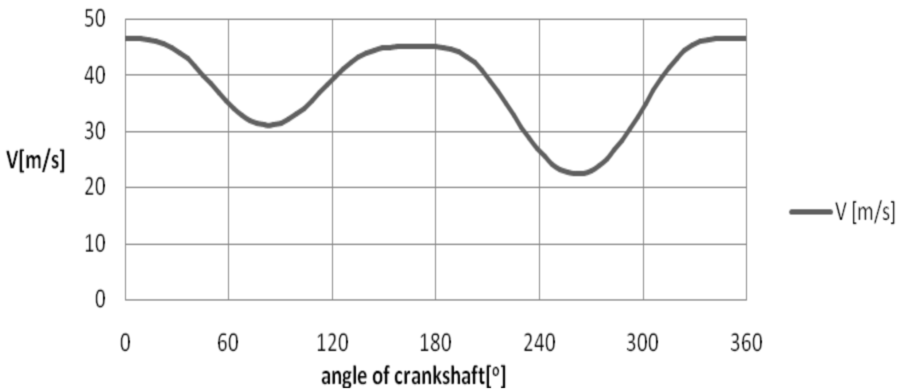

Figure 8**:** *Absolute velocity of piston at 3000 rpm (velocity which the piston moves through engine housing)*

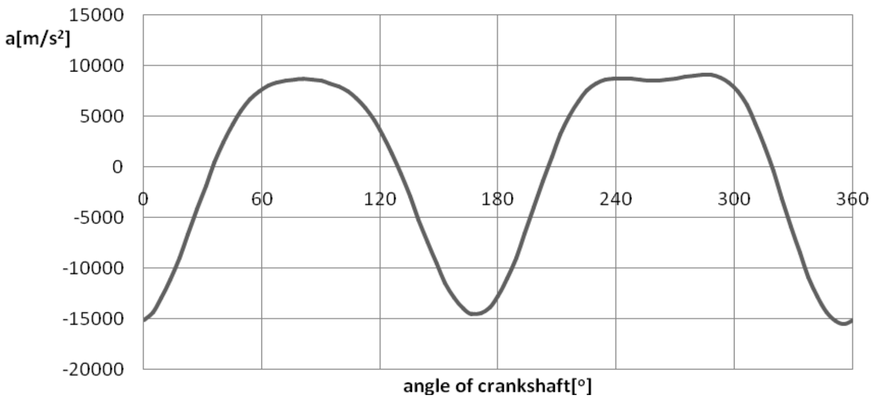

Figure 9: *Relative acceleration of piston at 3000 rpm*

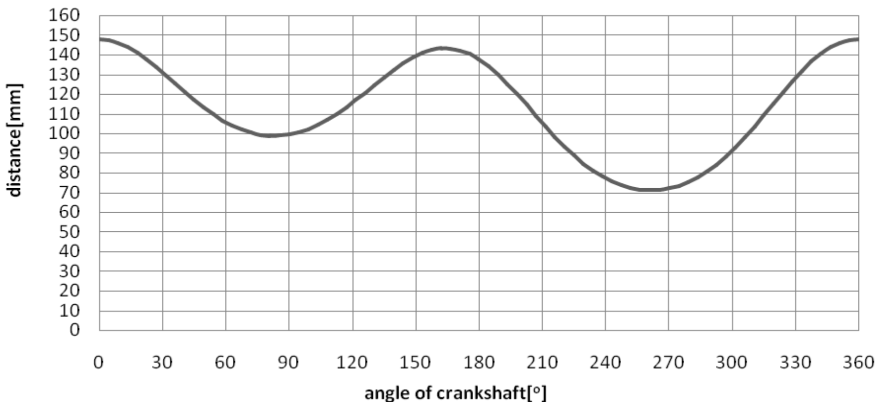

Figure 10: *Distance from piston and rotation axis of rotor*

CONCLUSIONS

This paper deals with kinematics analysis of valveless IC engine with more complete expansion. Final results are shown through diagrams and charts. As can be seen from Fig. 3, in this engine piston in-plane motion are translated to rotary motion of crankshaft, unlike conventional IC engines where pistons have translatory motion. Also, it can be seen that apsolute piston velocity are greater than in usually IC engine (with the same number of cycles per time), but the changes of piston speed per time are smaller than in conventional engine. From diagram in Fig. 10 are described how with this kinematics piston distance have different values for compression and expansion stroke, this feature is very important because in this way working fluid can reach much lower temperature at the end of expansion. Lower temperature at the end of expansion means more efficiency. Through described kinematics IC engines easy can achieve thermodynamic cycles with increased efficiency.

ACKNOWLEDGMENTS

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REFERENCES

[1] Dorić J.: ''Valveless IC engine with more complete expansion'', Tractor and Power machines, Volume 14, Issues 2/3, p. 58-64.

[2] Gruden D.:''Automobile development followed by prophency of ecological disasters'', Mobility and Vehicle Mechanics, Volume 34, Issues 3, p. 4.

[3] Gruden D.:''Technical measure to reduce carbon dioxide emissions on the road traffic'', Mobility and Vehicle Mechanics, Volume 32, Issues 3/4, p. 54-69.

[4] Merker G., Schwarz C., Stiesch G., Otto F.:''Simulating Combustion'', Springer-Verlag Berlin Heidelberg 2006, Germany.

[5] Klinar I.:''Motori sa unutrašnjim sagorevanjem'', Faculty of Technical Sciences, Novi Sad, 2009.

[6] Dorić J.:''Radial-rotary Valveless four-cycle IC engine with more complete expansion of the working group'', patent application number 2008/0607, at the Intellectual Property Office of the Republic of Serbia, Belgrade 2008.