# EFFECTS OF PISTON SPEED, COMPRESSION RATIO, AND CYLINDER GEOMETRY ON SYSTEM PERFORMANCE OF A LIQUID PISTON

by

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*Energy storage systems are being more important to compensate irregularities of renewable energy sources and yields more profitable to invest. Compressed air energy storage systems provide sufficient of system usability, and large scale plants are found around the world. The compression process is the most critical part of these systems and different designs must be developed to improve efficiency such as liquid piston. In this study, a liquid piston is analyzed with CFD tools to look into the effect of piston speed, compression ratio, and cylinder geometry on compression efficiency and required work. It is found that, increasing piston speeds do not affect the piston work but efficiency decreases. Piston work remains constant at higher than 0.05 m/s piston speeds but the efficiency decreases from 90.9 % to 74.6 %. Using variable piston speeds has not a significant improvement on the system performance. It is seen that, the effect of compression ratio is increasing with high piston speeds. The required power, when the compression ratio is 80, is 2.39 times greater than the power when the compression ratio is 5 at 0.01 m/s piston speed and 2.87 times greater at 0.15 m/s. Cylinder geometry is also very important because, efficiency, power and work alter by L/D, D, and cylinder volume, respectively.*

Key words: *liquid piston, energy storage, compressed air energy storage, computational fluid dynamics*

## Introduction

Renewable energy sources, such as Sun and wind energy, are a great option to traditional energy sources, and become more profitable, because energy prices are mounting and oil reserves are running out day by day. Nevertheless, energy production from renewable energy sources has an unsteady and unpredictable characteristic. Using a storage unit is a reasonable solution to compensate the irregularities of these sources. Batteries which are chemical energy storage systems and practiced often in many devices in our everyday life have inadequate specifications to meet the requirements of large scale applications. Consequently, mechanical energy storage systems like pumped hydro-energy storage and compressed air energy storage (CAES) are applied to regulate energy production from renewable sources. It is expected that CAES systems will be useful for grid integration of renewable energy sources. A new CAES system is developed called advanced adiabatic CAES, in order to remove external

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energy during the expansion process and improve system efficiency. The aim of this design is to compress air under adiabatic conditions and store the heat that generated in the compression process, and use it to heat the air during expansion thus external energy is not required any more [1-3, 4, 5]. Another encouraging design which avoids fuel need and improves system performance is iso-thermal CAES, where compression and expansion processes take place under constant temperature [6-8]. Liquid piston is an attractive research area and some companies which focus on this technology, were founded to build iso-thermal CAES plants [9, 10]. Liquid piston design can be modified by adding rods in the compression chamber to increase heat transfer between air and liquid [11, 12]. Determination of the system performance can be evaluated by heat transfer methods, energy and exergy analysis, and CFD tools. Kim *et al.* [7] calculated energy and exergy flows of different types of CAES systems and specified the system efficiencies. Saadat *et al.* [11] optimized the compression and expansion velocities to increase the efficiency and obtain a 40% rise in compression efficiency. Zhang *et al.* [12] showed that using CFD codes could be a good method to predict temperature and pressure in a piston during compression. Van de Ven and Li [13] compared the liquid piston and reciprocating compressor, and found that liquid piston efficiency is higher than that of reciprocating compressor. Hybrid CAES systems co-operating with other energy storage technologies like super-capacitors and batteries, were also developed to enhance system performance [14, 15].

In this work, 2-D simulations were done to examine the operation of a liquid piston during the compression process. The effect of piston speed, compression ratio, and cylinder geometry on energy efficiency and required power for compression stage was investigated. It is found that, higher piston speeds and compression ratios increase required power and decrease efficiency. Variable piston speeds as a function of cylinder pressure are also studied and it is seen that working with variable piston speeds has a slight effect on system efficiency and required power. When the effect of cylinder geometry was examined it is found that efficiency is highly related to *L/D* ratio and power is highly related to *D* only.

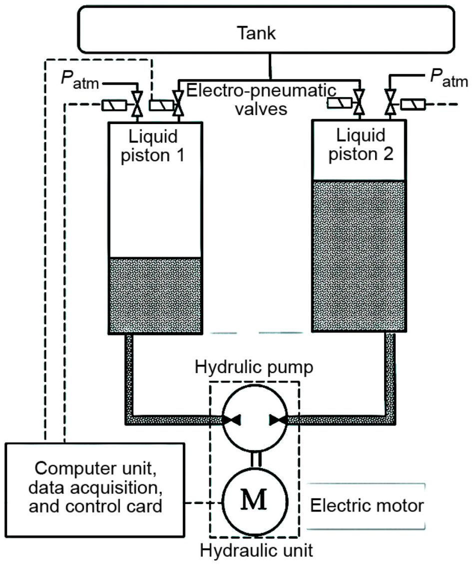


**Figure 1. Components of a small scale CAES system with liquid pistons**

Compression stage is one of the important processes of a CAES system and one way to make it more effective is compressing air with liquid piston where the near iso-thermal process occurs. Piston speed, geometry, and working pressure ranges have to be well designed before construction to make the system more profitable.

## Basic concepts of a CAES system with liquid pistons

The main objective of a CAES system with liquid pistons is to compress air under iso-thermal conditions, thus it requires less energy for compression and system, and compression efficiency can be improved. A simple CAES system consists of a pump, an electrical motor, two liquid pistons, a storage tank, and flow control valves (fig. 1). The fluid (oil, water, *etc.*) is pumped by an electric motor driven pump into the pistons where the piston air is at atmospheric pressure. The air pressure increases with the fluid level increment in the pistons up to tank pressure. When the piston pressure balanced with the tank pressure, the valve between the piston and the storage tank is opened and compression process continues till fluid level in pistons reaches the upper limit. While one piston compresses air the other one is filled with air by opening the valve between the piston and ambient air and the fluid level decreases since the fluid is pumped into the other piston. The electrical energy, consumed in electric motor to drive the pump, is converted to mechanical energy and stored in a tank by compressing air. The storage capacity of the system can be easily improved by increasing the tank pressure or tank volume. The piston speed, which is highly effective on air pressure and temperature inside the piston, can be set by adjusting flow rate of the pump. The piston speed is relatively slower compared to a reciprocating compressor in order to obtain iso-thermal conditions. Piston speed is assumed around 0.2 m/s in both numerical and experimental studies to investigate the iso-thermal compression process [12, 16]. Lower piston speeds also reduce the power input and allow high compression ratios with less energy consumption.

## Material and method

In this study the commercial CFD code ANSYS FLUENT software was used for the transient 2-D fluid flow and heat transfer field analysis with the moving mesh. FLUENT software solves continuum, momentum, energy, and transport equations numerically. A complete details of the mathematical model is not given here for the sake of brevity, instead, a brief account is given only. However, the details of the mathematical model can be found in [12, 17]. In the numerical solution, second order discretization method was used for convection terms. The PISO scheme was applied for pressure-velocity coupling and PRESTO! was used for spatial discretization of pressure term [12, 17]. Since the piston geometry is symmetric with respect to the axis in the cylinder as seen in fig. 2, the numerical computations were performed by using the 2-D axisymmetric cylindrical co-ordinates. Because of low piston speeds, laminar flow model was used as viscous model. Air was assumed as an ideal gas. Convergence criteria were set to $1 \cdot 10^{-5}$ for continuity, $x$-momentum and $y$-momentum and it was set to $1 \cdot 10^{-9}$ for energy. Time step size was adjusted to 0.01 seconds and was kept constant during calculations.

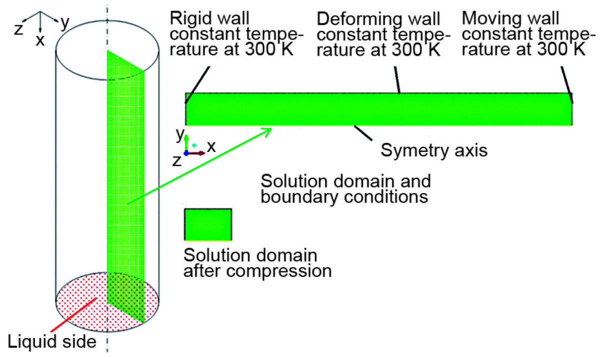


**Figure 2. Solution domain and the boundary conditions of the model**

We assumed that all walls were kept at 300 K constant temperature during simulations because the cylinder boundaries do not warm up due to large wall thickness and long compression time that provides enough time to heat transfer. Boundary conditions are shown in fig. 2. Piston surface which is an interface between air and liquid was assumed as a moving wall and movement of the wall was defined using user defined functions tool of the FLUENT.

The system performance was investigated by calculating two significant parameters system efficiency and required power for compression stage. The system efficiency was defined as ratio of ideal required work which occurs in iso-thermal compression to actual work done by piston:

$$\eta = \frac{W_i}{W_a} \tag{1}$$

The iso-thermal compression work, $W_i$, was calculated by [18]:

$$W_i = P_1 v_1 \ln \frac{v_2}{v_1} \tag{2}$$

where $v_1$ and $v_2$ are the initial and final cylinder volume during compression, respectively, $P_1$ – the initial cylinder pressure, the value was 101325 Pa for all cases. Actual piston work, $W_a$, was calculated by sum of $P_a \Delta v$ product:

$$W_a = \sum P_a \Delta v \tag{3}$$

Power is defined by dividing actual piston work, $W_a$, to total required time for compression, $t$:

$$\text{Power} = \frac{W_a}{t} \tag{4}$$

In simulations, six different constant piston speeds are determined to investigate the piston speed effect on system performance. The results are given by non-dimensionalized speeds, $V^*$, which are divided to minimum speed, 0.01 m/s. The $V^*$ values used in the simulations are 1, 3, 6, 9, and 12. Other important parameter that affects system performance significantly is the compression ratio, eq. (5). Five different compression ratios are studied in this work, which are 5, 10, 20, 40, and 80. Different combinations of length and diameter are studied to investigate the geometry effect of the cylinder. Three different cylinder lengths (0.6 m, 1.2 m, and 2.4 m), and diameters (0.1 m, 0.2 m, and 0.3 m), were used. In this study, dimensions of the cylinder was selected as $L = 1.2$ m and $D = 0.2$ m, and compression ratio was taken as 10:

$$r = \frac{P_2}{P_1} \tag{5}$$

Variable piston speeds, which are the function of the cylinder air pressure, are also investigated. Two functions are used to define piston speed. One is the linear function, eq. (6), and the other one is quartic function, eq. (7):

$$V = V_{\max} - \frac{V_{\max} - V_{\min}}{P_{\max} - P_{\min}} (P_{\max} - P_a) \tag{6}$$

$$V = V_{\max} - \frac{V_{\max} - V_{\min}}{P_{\max}^4 - P_{\min}^4} (P_{\max}^4 - P_a^4) \tag{7}$$

where $V_{\max}$ and $P_{\max}$ represent the maximum piston speed and cylinder pressure, respectively, and the $V_{\min}$ and $P_{\min}$ – the minimum piston speed and cylinder pressure, respectively. Compression processes were started at atmospheric pressure, thus $P_{\min}$ was $1.01325 \cdot 10^5$ Pa for all cases, and $P_{\max}$ was changed according to compression ratio. Seven different $V_{\min}$ and $V_{\max}$ combinations were tested to compare results with constant piston speed (tab. 1).

Four different mesh sizes are used to determine the suitable grid for problem. Number of grid points for both axial and radial direction of these mesh sizes are given in tab. 2.

Figure 3 represents the pressure solution of these four different mesh sizes. As seen in the figure, pressure data were very close to each other, thus a five second period of the compression was given for better comparison between grids. Grid 3 was used in simulations to reduce computation time and more accurate results. This mesh sizes were applied to simulations where cylinder length, $L$, and diameter, $D$, were 1.2 m and 0.2 m, respectively. For different sized cylinder geometry, ratio of grid points to length based on grid 3 was used for meshing.

Simulation results were validated by an experimental set-up with a 1.2 m length and 0.2 m diameter cylinder. In experiments piston speed was set to 0.03 m/s and remains constant during compression. Pressure data were recorded by a transducer which is located at top of the cylinder. As seen in fig. 4, simulation results showed a good agreement with experimental data.

**Table 1. The $V_{max}$ and $V_{min}$ combinations for variable piston speeds**

| | $V_{max}$ | $V_{min}$ |
|---|---|---|
| Case 1 | 0.15 | 0.01 |
| Case 2 | 0.12 | 0.01 |
| Case 3 | 0.09 | 0.01 |
| Case 4 | 0.15 | 0.03 |
| Case 5 | 0.15 | 0.06 |
| Case 6 | 0.18 | 0.01 |
| Case 7 | 0.21 | 0.01 |

**Table 2. Number of grid points of different mesh sizes**

| Grid | Number of points | |
|---|---|---|
| | Radial direction | Axial direction |
| Grid 1 | 10 | 120 |
| Grid 2 | 20 | 240 |
| Grid 3 | 40 | 480 |
| Grid 4 | 80 | 960 |

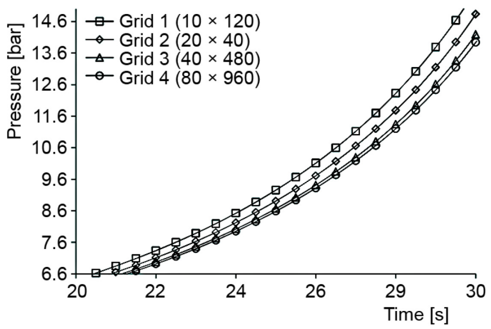


**Figure 3. Pressure values of different mesh sizes during compression**

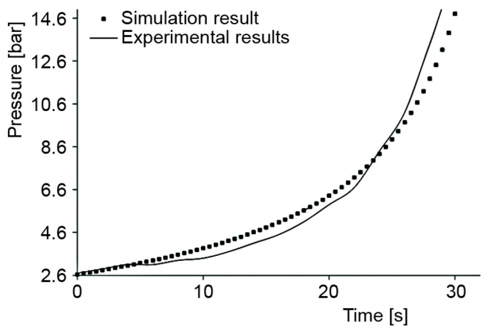


**Figure 4. Comparison of experimental data with simulation results**

## Results

### *Effect of piston speed*

It is obvious that faster compression process needs more power, however, required piston work in a compression process does not show a remarkable change with speed. Thus power is only relevant to compression time so variation of the piston work with speed is linear, figs. 5(a)-(b). On the other hand, efficiency decreases despite piston work does not change remarkably because $W_i$ is decreasing according to eq. (2). The compression process is being closer to isentropic process while increasing piston speed, thus it can be reached to final pressure that is defined by compression ratio, at bigger cylinder volume, and $W_i$ decreases. Conditions in the cylinder do not vary considerably at faster than 0.05 m/s piston speeds so piston work remains constant.

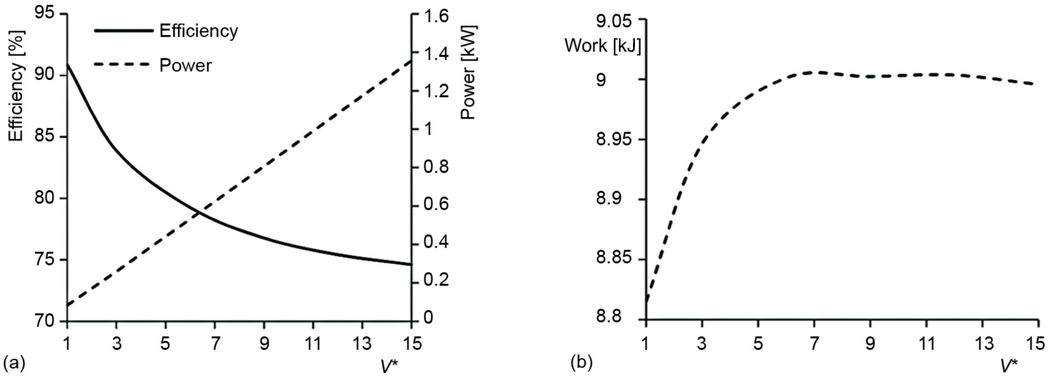


**Figure 5. Variation of energy efficiency, power (a) and piston work (b) with non-dimensioned speed**

The main purpose of using variable piston speeds is to reduce compression work and increase efficiency by decelerating piston speed at higher pressure. With this approach, compression starts at maximum speed, $V_{max}$, while piston pressure is $P_{min}$ (101325 Pa), and ends at minimum speed, $V_{min}$, while piston pressure is $P_{max}$. Speed variation is defined by two functions a linear, eq. (6), and a quartic, eq. (7), which their input is cylinder pressure. Starting piston speed, $V_{max}$, is very important in both cases, and decreasing $V_{max}$ improves system efficiency considerably, fig. 6. But the change in efficiency is not remarkable compared to the constant piston speed, furthermore, efficiency decreases when variable piston speed is defined by a quartic function. On the other hand, using variable piston speeds reduces the piston work while efficiency is decreasing due to final cylinder volume, $v_2$, as mentioned previously.

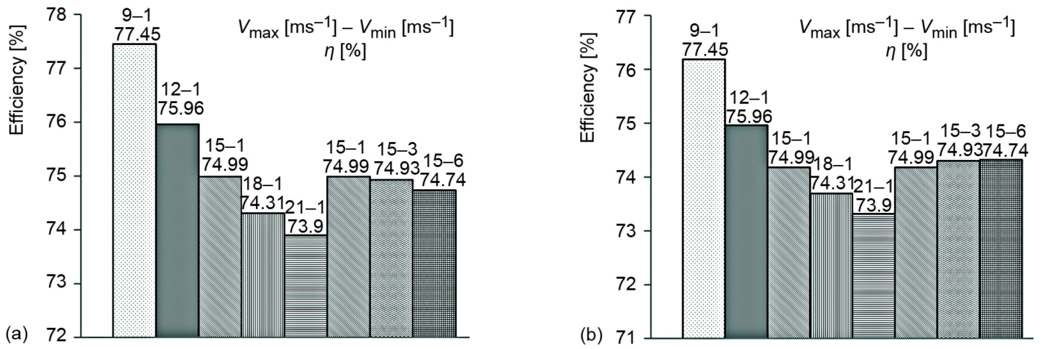


**Figure 6. System efficiencies for variable piston speeds that calculated by the linear function (a) and quartic function (b)**

*Effect of compression ratio*

The compression ratio is one of the major parameter that defines system performance. Higher compression ratios mean more stored energy, but lower efficiencies due to rise in work done by piston according to eq. (3), fig. 7.

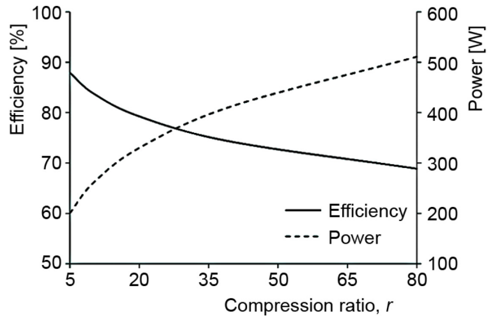


**Figure 7. Efficiency and power variation with compression ratio**

The required power is highly related to piston speed and has a linear relation with speed. The power is not affected significantly by compression ratio in low piston speeds, fig. 8(a). The reason is that compression time is long enough, even the piston work is quite different in low piston speeds where power is defined by total compression time, fig. 8(b). Compression process has slightly varied by the piston speed at low compression ratios, and it can be said that compressing air with higher piston speeds will be useful at under compression ratio 20.

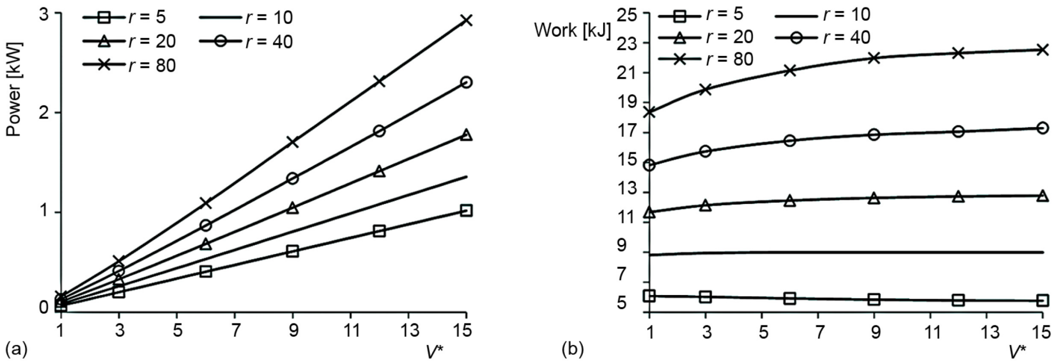


**Figure 8. Power and piston work variation with *V****

*Effect of cylinder geometry*

System performance is highly concerned with cylinder geometry while piston work is a function of the air mass, therefore, compressing more air needs more energy. Cylinder length, *L*, can be represented by piston speed since volume derivation, $\Delta v$, is constant when piston speed is constant. Hence the required power varies only with cylinder diameter, *D*, and piston speed, fig. 9(a). The piston work is higher in long cylinders, on the other hand, in short cylinders required work is lower, but time is also shorter than long cylinders then the power remains constant. It is seen that, system efficiency is related to *L/D* which affects heat transfer rates from surfaces, fig. 9(b). The principally heat transfer rate can be defined by using air volume per heat transfer area which is close to *D/4*. In other words, heat can be transferred from surfaces more effectively in small diameter cylinders. The *L* is also important for surface area and then it is clear that efficiency, temperature and heat transfer rates are significantly related with *L/D*.

## Conclusions

One of the useful tools to compress air iso-thermally is liquid piston where air is pressed by a liquid like water or oil in a tank. Many parameters affect the iso-thermal process,

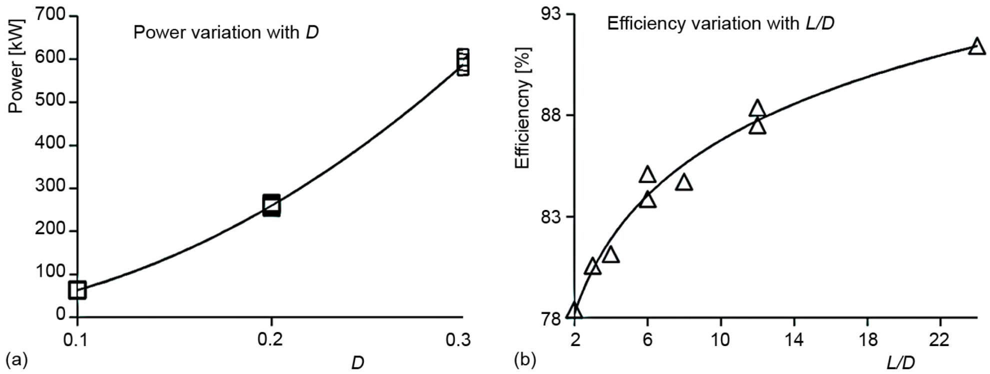


**Figure 9. Power and efficiency variation with geometric parameters**

hence system performance is likewise determined. In this work, the effect of piston speed, compression ratio, and cylinder geometry on compression efficiency and required power is investigated by 2-D CFD simulations. The CFD model of the compression process shows a full correspondence with experimental data and can be employed to determine the liquid piston characteristics confidently.

The primary parameter that affects the efficiency directly is the piston speed where efficiency decreases at higher piston speeds despite little changes in work. On the other hand, work does not remain constant at higher compression ratios and more power is required at higher speeds to accomplish the compression process in a shorter time. Variable piston speeds that defined by pressure is not an effective way to improve system performance, while only an average 0.533 point rise was shown in efficiency.

System efficiency and power is significantly connected to compression ratio where higher compression ratios cause a reduction in efficiency from 87.93 % to 68.89 %, and power is increasing by 2.55 times. The effect of compression ratio is increasing with high piston speeds.

It is also found that the cylinder geometry is very important parameter where efficiency, power and work alter by *L/D*, *D*, and cylinder volume, respectively. It is recommended to use long cylinders with small diameters for better compression efficiency. Efficiency can be improved up to 91.42 % by only modifying the cylinder dimensions.

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## Nomenclature

$D$ – cylinder diameter, [m]
$L$ – cylinder length, [m]
$P_1$ – initial cylinder pressure, [Pa]
$P_a$ – actual cylinder pressure, [Pa]
$P_{atm}$ – atmospheric pressure, [Pa]
$P_{max}$ – maximum cylinder pressure, [Pa]
$P_{min}$ – minimum cylinder pressure, [Pa]
$r$ – compression ratio, [–]
$t$ – time, [s]
$V$ – piston speed, [ms$^{-1}$]
$V^*$ – non-dimensionalized speed, [–]
$V_{max}$ – maximum piston speed, [ms$^{-1}$]
$V_{min}$ – minimum piston speed, [ms$^{-1}$]
$v_1$ – initial cylinder volume, [m$^3$]
$v_2$ – final cylinder volume, [m$^3$]
$W_a$ – actual work done by piston, [J]
$W_i$ – iso-thermal compression work, [J]

*Greek symbol*

$\eta$ – system efficiency, [%]

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