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Improvement in part-load performance of a manifold injected spark ignition engine – an experimental investigation

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This paper deals with the experimental investigations carried out on a single-cylinder, four-stroke, manifold injected spark ignition engine to improve the part-load performance and emission characteristics by modulating the inlet valve closure timing (IVCT) and clearance volume (CV). The IVCT is delayed in order to reduce the volumetric efficiency of the engine with full throttle operation which in turn reduces the brake power output so that engine can be operated at part-load. In addition, the CV is also reduced with respect to IVCT to maintain the effective compression ratio (ECR) of the engine. These things change the geometric expansion ratio (GER) and ECR of the engine along with reduced pumping losses to increase the brake thermal efficiency and reduce the exhaust emissions at part-loads. In order to vary the part-load brake power output, a suitable combination of the IVCT and CV is used which in turn vary the GER/ECR ratio of the engine. In this study, experiments are carried out for the different GER/ECR ratios varying from 1.25 to 2 with two ECRs of 7 and 8 at a constant engine speed of 1500 rev/min. From the results, it is found that for GER/ECR ratio of 1.5 with ECR of 8 and 7, the improvement in brake thermal efficiency is about 3.5 and 6.6%, the reduction in unburned hydrocarbon emissions is about 25 and 22.5% and the reduction in nitric oxides emissions is about 51 and 52% respectively compared to conventional engine at the corresponding brake power outputs.

Keywords: Extended expansion engine, Manifold injection, Spark-ignition engine, Part-load performance

Today, internal combustion (IC) engine is the main source of power for the transportation sector and is also responsible for a substantial fraction of fuel consumption and exhaust emissions. The scarcity of oil resources and the ever-increasing standards on exhaust emissions have dictated a need for the more efficient and less polluting IC engines. There are three important efficiency terms associated with IC engines during the conversion of heat energy into mechanical work, viz. (i) mechanical efficiency, the extent to which the friction and other mechanical losses are associated with energy conversion and is in the range of 80-90%, (ii) combustion efficiency, the extent to which the energy release takes place from the combustion of fuel and is in the range of 90-95%, and (iii) cycle efficiency, the extent to which energy released by the fuel is converted into mechanical work and is in the range 40-50%[1-5].

Among the above three efficiencies, there seems to be a good scope for improving the cycle efficiency by some simple means. The cycle efficiency depends upon work done during a cycle, which is proportional to the area under the pressure-volume (*p*-*V*) diagram and the heat input during a cycle. It is possible to increase the area under the *p*-*V* diagram by reducing the pumping and blow down losses by means of extended expansion[3]. In conventional spark ignition (SI) engines, ECR is equal to GER and GER/ECR ratio is equal to one[3]. Also, in these engines, load is controlled by throttling, which leads to low part-load brake thermal efficiency. It is possible to operate the SI engine at part-loads by delaying the IVCT, which will reduce the volumetric efficiency of the engine by pushing some of the charge out of the cylinder and correspondingly reduce the brake power output. However, in doing so, the ECR of the engine reduces which adversely affects the brake thermal efficiency. However, it is possible to maintain the original ECR by suitably reducing the CV in addition to the delayed IVCT. This results in increasing the GER alone, while maintaining the original ECR and makes the GER/ECR ratio of the engine to become more than one. This type of engine is called as an extended expansion engine. The principle of extended expansion engine is based on Otto-Atkinson cycle[1]. In the extended expansion engine, when the IVCT and

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CV are changed in order to vary the GER/ECR ratio, the engine volumetric efficiency reduces. This will reduce the brake power output of the engine even at the full throttle operation. However, this could be used for achieving better part-load performance with full throttle operation[6-9]. In addition, the exhaust emissions could be expected to reduce because of the availability of more time for oxidation of the exhaust gases due to longer expansion. However, in practice the IVCT and CV have to be changed dynamically with respect to the engine load to obtain the best possible results.

The main aim of the gasoline injection in four-stroke SI engines is to combine the advantage of high specific power at full-load as in SI engine with high part-load efficiency as in diesel engine. At present, there are two types of gasoline injection systems used in SI engines. In the first type, the gasoline is injected into the inlet manifold or over the inlet valves known as manifold or port fuel injection system respectively. In the second type, gasoline is injected directly into the cylinder known as direct gasoline injection (GDI)[10-13]. In both these types, the power output of the engine is controlled by varying the quantity of gasoline injected.

The extended expansion engine has the advantages like: (i) improved cycle efficiency due to reduced pumping losses, (ii) more power output due to extended expansion, and (iii) reduced exhuast emissions[1-5]. Also, gasoline injected engine has the following advantages: (i) higher compression ratio and the possibility of using low octane fuels due to charge cooling during injection, (ii) fuel cut-off during vehicle deceleration and (iii) high volumetric efficiency[10,14,15].

In the past, the extended expansion concept was not adopted into production engines because of complexity of the variable valve timing mechanism and also due to non-availability of fast responsive mechanism. In this study, the advantages of both the extended expansion and gasoline injection concepts are combined to develop a gasoline injected extended expansion engine (GIEEE). The GIEEE is expected to have good part-load thermal efficiency with reduced emissions and full-load power output.

Experimental Procedure

The schematic diagram of the experimental set-up is as shown in Fig. 1. The engine used is a conventional single-cylinder, air-cooled, vertical, four-stroke SI engine. The specifications of the engine are shown in Table 1. The engine is basically a diesel engine with maximum speed of 1500 rev/min. A diesel engine (CR = 17.5) is selected in order to have flexibility to alter the CV with respect to IVCT. The above engine is modified in order to run in the manifold fuel injected SI mode. A fuel injection system consisting of a throttle body, a solenoid operated fuel injector, a fuel storage tank, a rail, an electric fuel pump, a pressure regulator, a pressure

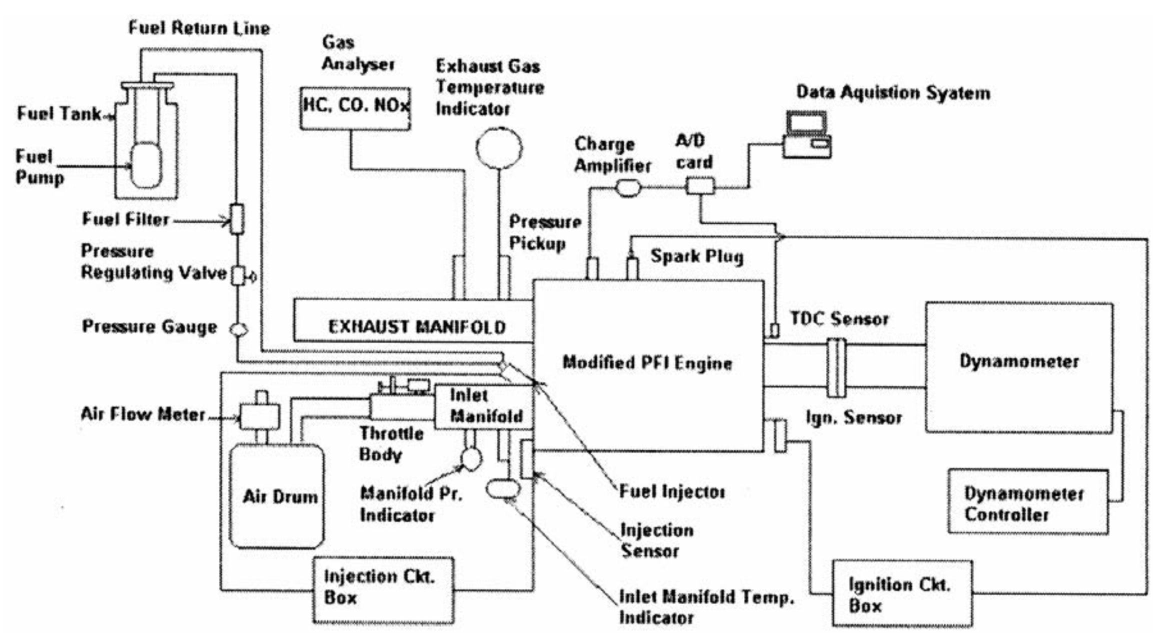

Fig. 1— Schematic diagram of the experimental set-up

gauge and an in-house control circuit are used. It is possible to control the injection timing and duration in the fuel injection system to vary the air-fuel ratio of the mixture supplied to the engine. The control circuit receives signals from a sensor mounted on the camshaft of the engine to start the injection. Injection duration is varied by the period of excitation given to the fuel injector. Another electronic circuit is developed in-house and used to control the ignition timing of the capacitive discharge ignition system, which is triggered by another sensor mounted on the flywheel to produce the spark. The ignition timing is controlled by electronically delaying the triggering signals after recieveing the sensor signals. A top dead center (TDC) sensor is mounted on the crank-shaft to produce the TDC signals which are acquired through an analog to digital (A to D) card onto a PC for data storage.

The engine is coupled to an eddy current dynamometer to measure the speed and torque of the engine. Suitable instruments are connected to the engine to measure air flow, fuel flow, exhaust gas temperature, inlet manifold temperature and pressure. Provisions are made in the exhaust manifold to take the exhaust gas samples to measure the emissions. A piezo-electric pressure pickup is mounted on the cylinder head to acquire the in-cylinder pressure data which are also acquired through an A to D card and stored onto the PC along with TDC signals for further processing.

The experiments are conducted at a constant engine speed of 1500 rev/min, and at two ECRs of 8 and 7 and at four GER/ECR ratios of 1.25, 1.5, 1.75 and 2.0. Engine is motored at all the configurations of the conventional and GIEEE. Here, a low speed operation is selected because the engine's maximum speed is 1500 rev/min and also the aim of the present study is mainly to prove the concept. The load is varied from zero to full level in definite steps by varying both the throttle position and quantity of gasoline injected. At full-throttle operation, the engine is operated at an air-fuel ratio of 17:1. However, at low loads, the air-fuel ratio is adjusted for misfiring limit. At every point of operation, the spark timing is adjusted to minimum advance for best torque (MBT). However, at full loads, the spark timing is adjusted for knock-free operation.

Table 1— Engine Specifications

Type	Single cylinder, air cooled, vertical, SI engine
Bore	87.5 mm
Stroke	110 mm
Displacement	661.45 cm^3
Connecting rod length	232 mm
Bumping clearance	0.9 mm
Compression ratio	8:1
Rated power	4.4 kW at 1500 rpm
Rated speed	1500 rpm
Inlet valve opening	4.5^0 bTDC
Inlet vale closing	35.0^0 aBDC
Exhaust valve opening	35.0^0 bBDC
Exhaust valve closing	4.5^0 bTDC

Note: Above engine was operated as conventional manifold gasoline injection and GIEEE mode

Results and Discussion

The main aim of this study is to show the effect of IVCT and CV on the performance and emission characteristics of the GIEEE. In the following discussion, conventional or standard engine refers to standard manifold injected SI engine with GER/ECR ratio equal to one. Figures 2-7 show the important performance and emission characteristics for ECRs of 8 and 7 at 1500 rev/min, for different configurations of the GIEEE. As a first step towards the experiments, motoring tests are conducted for both the conventional engine and GIEEE at all the configurations. The volumetric efficiency under motoring conditions is used for the calculation of CV, ECR and to fix the IVCT of the GIEEE[2]. The IVCT and CV are adjusted such that the peak pressure under motoring conditions is very much closer to that of the conventional engine at the corresponding ECR. During the experiments, it was observed that the peak pressure of conventional engine and GIEEE under motoring conditions were almost equal indicating almost a constant ECR at all the configurations.

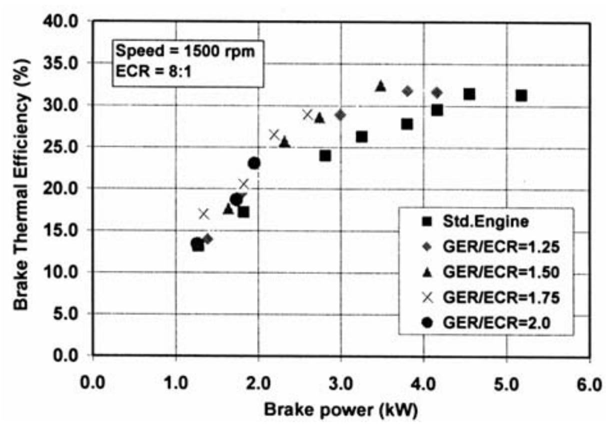

Fig. 2— Variation of brake thermal efficiency with brake power

The variation of brake thermal efficiency with brake power for GIEEE for all the configurations with ECR of 8 are shown in Fig. 2. In this figure, brake thermal efficiency of the conventional engine is also plotted for comparison (GER/ECR = 1). From Fig.2, it can be observed that, at all the brake power outputs, brake thermal efficiency of the GIEEE is higher compared to that of the conventional engine. Also, it is observed that, with increase in GER/ECR ratio, the engine derating takes place at full-load operation because of the reduction in volumetric efficiency. The brake power output of GIEEE at ECR of 8 and 7, at 1500 rev/min, for GER/ECR ratios of 1.25, 1.5, 1.75 and 2.0 is about 80.3, 67, 50 and 38% respectively with respect to standard engine. However, at this condition, the engine is operating at full throttle with higher brake thermal efficiency. This is the main advantage of adopting GIEEE concept. In addition, it can be observed that the difference in brake thermal efficiency between the two engines increases with increase in GER/ECR ratio. It may be mainly attributed to the reduction in pumping losses and prolonged expansion in GIEEE at higher GER/ECR ratio.

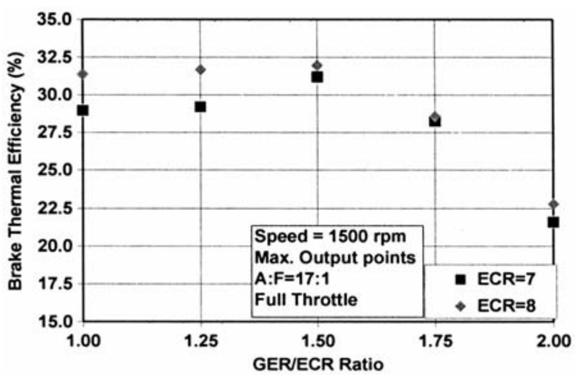

Fig. 3— Variation of brake thermal efficiency with GER/ECR ratio at maximum output points

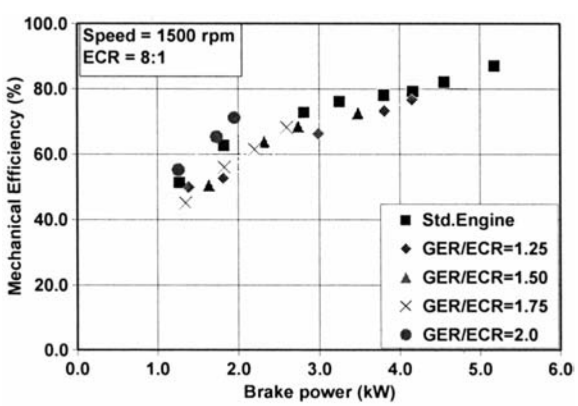

Fig. 4— Variation of mechanical efficiency with brake power

Figure 3 shows variation of brake thermal efficiency with GER/ECR ratio at maximum brake power output points. From Fig.3, it is observed that, at GER/ECR ratio of 1.5 and ECR of 8, the brake thermal efficiency is close to 32.5% as against the conventional engine's brake thermal efficiency of about 31.4%. The error in the calculation of the brake

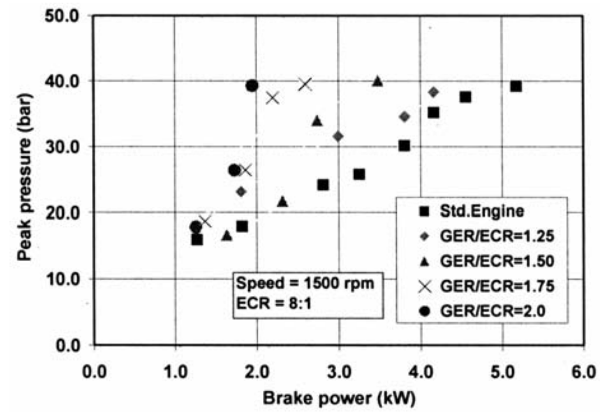

Fig. 5— Variation of peak pressure with brake power output

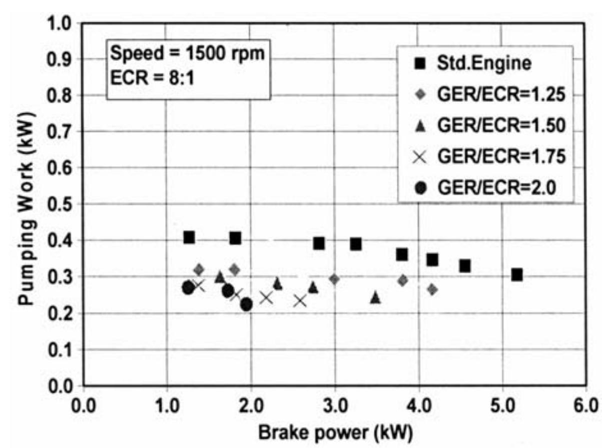

Fig. 6— Variation of pumping power with brake power output

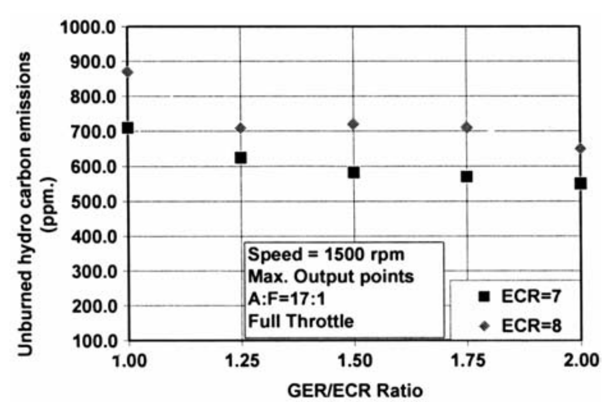

Fig. 7— Variation of unburned hydrocarbons emissions with GER/ECR ratio at maximum output points

thermal efficieny is about 0.7%. Therefore, there is an improvement of about 3.5% in brake thermal efficiency at an ECR of 8 for GIEEE. Similarly, at an ECR of 7, there is an improvement of about 6.6% which is considered to be quite good. From Fig. 3, it is observed that, at an ECR of 7, the improvement in brake thermal efficiency is more. This may be attributed to the reduction of mechanical efficiency at ECR of 8 compared to that of ECR of 7[2,3].

Figure 4 shows the variation of mechanical efficiency with brake power output at ECR of 8. Generally, it is seen that, the mechanical efficiency of the GIEEE is less than that of conventional engine at the corresponding brake power output except for GER/ECR ratio of 2. The main reason for this may be attributed to the reduction in brake power in case of GIEEE at lower GER/ECR ratio.

At all the loads, the percentage of indicated power required to over-come the friction remains the same for constant speed operation and hence, mechanical efficiency depends upon the load. Therefore, the mechanical efficiency of the GIEEE at the corresponding brake power output reduces compared to the conventional engine. However, the mechanical efficiency at GER/ECR ratio 2 is more than that of the conventional engine. This may be attributed to the fact that, the friction increases approximately as a linear function of cylinder pressure[16]. The cylinder pressure at the beginning of the compression stroke is atmospheric until the closure of inlet valve unlike the conventional engine. Also, though the peak pressure in case of GIEEE is higher than that of the conventional engine at low loads as shown in Fig. 5, pressure towards the end of expansion process is lower than that of the conventional engine due to longer expansion. At GER/ECR ratio 2, IVCT is 135° after bottom dead center (aBDC), a large percentage of the piston stroke is covered during the compression process at nearly atmospheric pressure and also, during the late expansion stroke, the cylinder pressure is nearly atmospheric. These factors might have caused the improvement in mechanical efficiency for GIEEE at GER/ECR ratio of 2 compared to the conventional engine. Similar observations were made with ECR of 7 (not shown here).

Figure 6 shows the variation of pumping power with brake power output for ECR of 8. When the comparisons are made with the conventional engine at the corresponding brake power outputs, there is an appreciable reduction in pumping losses. For example, at ECR of 8 and GER/ECR ratio of 2, pumping power of the GIEEE is about 0.225 kW and brake power at full-throttle is about 1.95 kW, whereas for the conventional engine, at the same brake power, the pumping power is about 0.391 kW. Therefore, there is a reduction of about 42.5% in pumping losses of GIEEE compared to conventional engine.

Figure 7 shows variation of unburned hydrocarbon (UBHC) emissions with GER/ECR ratio at maximum output points. UBHC emissions are lower atECR of 7[17,18] compared to those of ECR of 8. Quenching of flame reactions by combustion chamber surfaces contribute to the ultimate appearance of UBHC in exhaust gases[19,20]. Considering the above factors, at ECR of 7, UBHC emission may be anticipated to be at lower levels, which is also true as seen in Fig. 7. However, when GER/ECR ratio is increased, CV is reduced which results in higher surface-to-volume ratio. Therefore, it might appear that, UBHC emission would increase at higher GER/ECR ratios. On the contrary, when GER/ECR ratio is higher, there is a longer expansion allowing more time for UBHC to oxidize. Hence, UBHC emissions at higher GER/ECR ratios depend upon the factor, which predominates among the above two. In this work, the latter one seems to be predominating, since total UBHC emissions are lower at higher GER/ECR ratios.

When ECR is reduced, CV will be increased which results in larger volume of residual exhaust gases[17]. Then the last part of the charge to be exhausted will be rich in UBHC[19]. Therefore, larger volume of residual gases results in increased UBHC emission in the exhaust. However, a low ECR engine would have high exhaust temperature and would promote oxidation of UBHC in the burned mixture resulting in low UBHC emissions[17,19]. These factors are responsible for reducing UBHC emission at ECR of 7 as it is evident from Fig. 7. From Fig.7, it can be seen that UBHC emissions decreases with increase in GER/ECR ratio. At GER/ECR ratio of 2, for ECR of 8 and 7, the reduction in UBHC is upto about 25 and 22.5% respectively compared to conventional engine at the corresponding brake power outputs.

Figure 8 shows the variations of nitric oxide (NO) emissions with GER/ECR ratio at maximum output points for all the configurations. It is observed that as GER/ECR ratio increases, the NO emissions decrease. This may be attributed to the fact that at full-load operation, the spark timing is retarded for knock-free operation. At GER/ECR ratio of 2, for ECR of 8 and

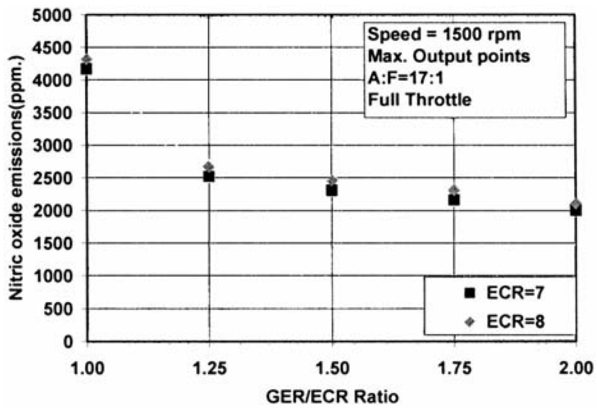

Fig. 8— Variation of nitric oxide emissions with GER/ECR ratio at maximum output points

7, the reduction in NO emissions is about 51% and 52% repectively compared to the conventional engine at the corresponding brake power outputs.

From the above results, it is evident that operating the manifold injected SI engine in an extended expansion mode is more beneficial from both performance and exhaust emissions point of view.

Conclusions

Following conclusions are drawn from the experimental investigations on GIEEE:

(i) At GER/ECR ratio of 1.5, for ECR of 8 and 7, improvement in brake thermal efficiency is about 3.5 and 6.6% respectively compared to that of conventional engine at the corresponding brake power outputs.

(ii) At GER/ECR ratio of 2 of GIEEE, for ECR of 8, there is a reduction of about 42.5% in pumping losses compared to that of conventional engine at the corresponding brake power outputs.

(iii) At GER/ECR ratio of 2 of GIEEE, for ECRs of 8 and 7, reduction in UBHC emissions is about 25 and 22.5% respectively compared to that of conventional engine at the corresponding brake power outputs.

(iv) At GER/ECR ratio of 2 of GIEEE, for ECRs of 8 and 7, reduction in NO emissions is about 51.4 and 52% respectively compared to that of conventional engine at the corresponding brake power outputs.

(v) The mechanical efficiency of the GIEEE at corresponding brake power output is lower than that of the conventional engine except for GER/ECR ratio of 2.

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