EXHAUST BRAKE SYSTEM MODEL AND TORQUE SIMULATION RESULTS ON A DIESEL SINGLE-CYLINDER ENGINE

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Abstract: *This paper deals with engine torque and cylinder pressure analysis for both combustion and braking operation. To modeling the auxiliary braking system it is used a butterfly valve which totally or partially obstructs the burning gases crossing section at the level of the exhaust manifold. Also for this purpose, we estimated the braking efficiency according to the influence of the exhaust manifold volume trapped between the exhaust valve gate and the butterfly valve. The single-cylinder diesel engine model is performed by means of GT Power software. The main conclusion of this paper is that by using an exhaust braking system, under some conditions, a higher value of retarding power can be obtained than the nominal engine power produced by engine in normal operating.*

Keywords: *exhaust brake, butterfly valve, engine torque, cylinder pressure, single-cylinder*

1. Introduction

Still as before the main mode of propulsion used in worldwide automotive industry stands the internal combustion engines. Over time, road vehicles have increased performance mainly due to: optimized body aerodynamics, reduced energy loss from the engine and the tire interface with running track. However, due to all these improvements, a reduction in native braking capacity has been achieved, which in case of heavy duty vehicles is absolutely necessary to by supplemented by the various auxiliary braking systems. If maintain actuated classic braking system for a longer period of time, in the case of heavy-duty vehicles, occurs a reduces braking efficiency by changing the physical properties of the friction material used and tires degradation due to the high level of heat released in this interface [Maxwell,1996].

Studies regarding the auxiliary braking systems are conducted that the highest braking efficiency is obtained with the engine brake systems right to [Manolache-Rusu, 2013, a], [Manolache-Rusu, 2013, b], [Manolache-Rusu, 2013, c] [Manolache - Rusu, 2013, d].But these have a much higher production price and it is use only for heavy road vehicles. For this reason, the most often encounter in the majority of transport vehicles, up to 7.5 tones, is a type of auxiliary braking system named exhaust braking , which is shown in Fig. 1.

Figure 1: *Exhaust brake with butterfly valve [2]*

This paper aims to determine the braking torque that can be achieved by fitting an auxiliary brake system on the exhaust manifold of a Lombardini 6LD400 single-cylinder engine.

2. Modeling single-cylinder engine in GT-Power software

Engine constructive and functional sizes used as entry data in this study are taken from the manufacturer's catalog data summarized in Table 1.

Table 1: *Lombardini 6LD400 constructive and functional sizes*

Piston diameter	86mm
Piston stroke	68mm
Engine displacement	395cm^3
Engine power	8hp
Compression ratio	18
large diameter of the exhaust valve pan	31mm
large diameter of the intake valve pan	35mm
angle of valve seat machining	45deg
connecting rod length	112mm
advance of the intake valve opening	7°CA
delay of the intake valve closing	26°CA
advance of the exhaust valve opening	21°CA
delay of the exhaust valve closing	3°CA
injection advance	25°CA

The modeling of the mono cylinder is made in the GT Power software and the block diagram of the model is shown in Fig. 2.

For this purpose, a series of templates have been customized by which the boundary conditions of the environment and the dimensions of the constructive and functional elements of the internal combustion engine have been imposed. The main templates used are: *EndEnvironment EngCylinder, Valve-CamConn PipeRound, InjProfileConn, ValveCamConn* and *EngineCrank-Train*.

Through the *EndEnvironment* template, *env-inlet1* and *env-outlet1* objects introduce the imposed values of absolute pressure, temperature, and environmental composition at the input and output of the engine.

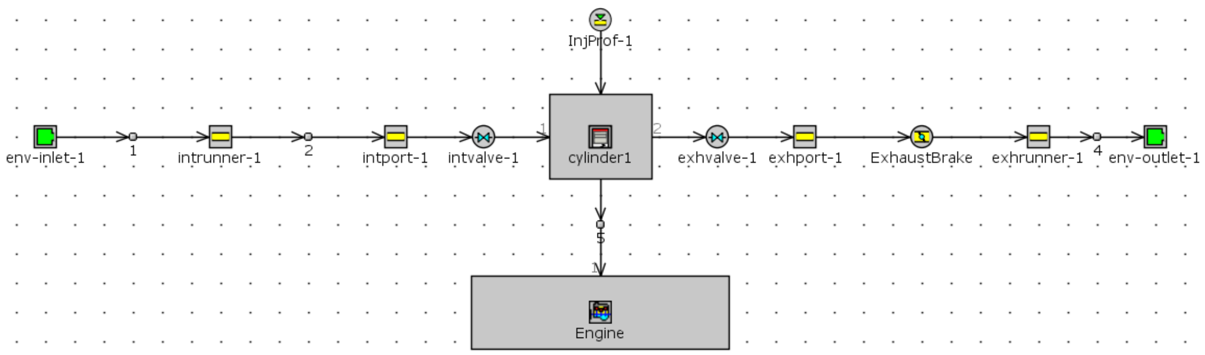


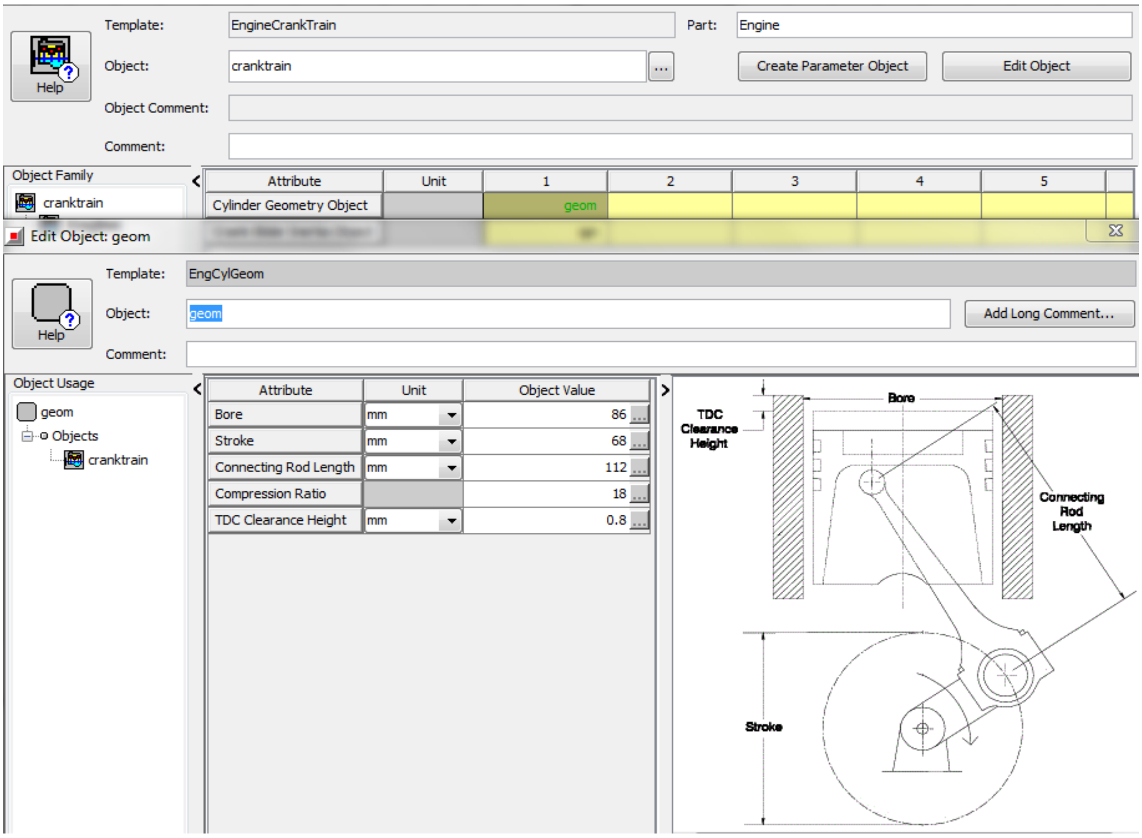
Figure 2: *Block diagram of the single cylinder engine*

In Fig. 3b), it is noted that the *outlet-reversing* value was chosen at the *Pressure Flag* attribute. This assumes that when a reverse flow occurs during the evacuation process, the ambient temperature at the close proximity of exhaust manifold will take value determined in the iterative process from the last iteration just before this change.

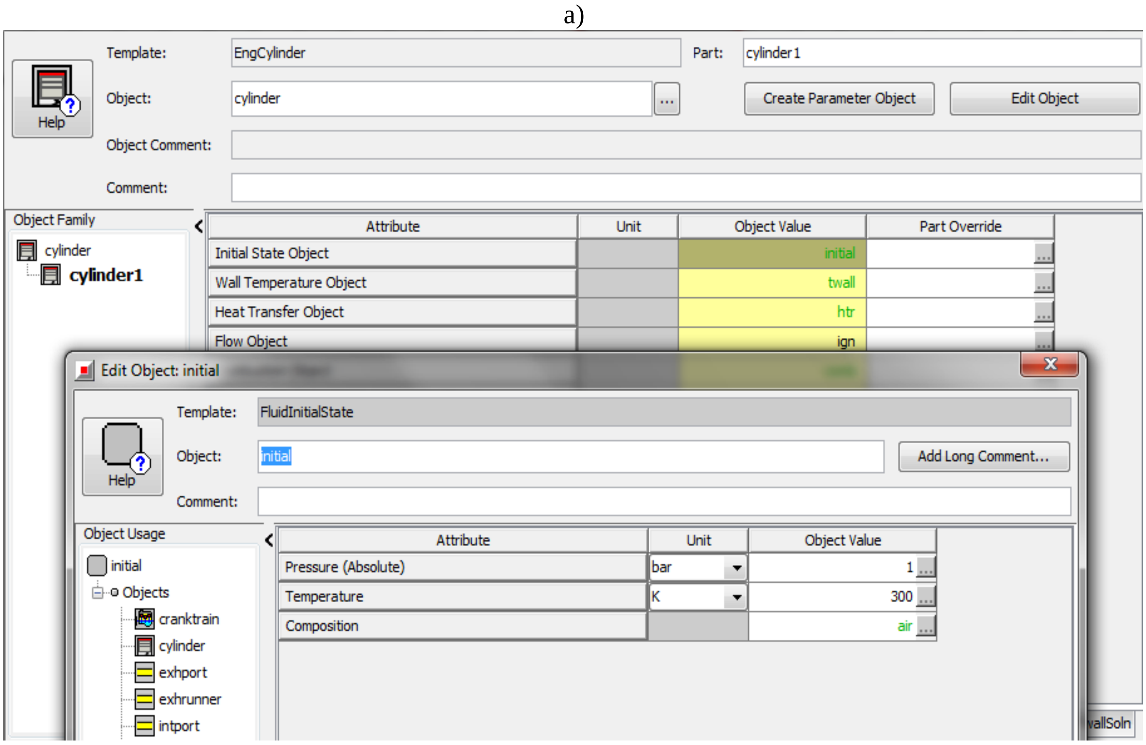
Using the *PipeRound* template, both the intake and exhaust ducts named *intrunner1*, *intport1*, *exhrunner1*, and also the *exhport1*, were modeled. Through the objects listed above are defined the constructive dimensions, the initial temperature of the pipe walls, the initial conditions of the working fluid and the precision of the results by specifying the meshing length.

Because we are interested in the evolution of engine torque according to influence of the exhaust manifold volume between the exhaust valve gate and the exhaust butterfly valve we will define within the object *exhport1* the parameter [L]. If the diameter of the pipe remains constant, through this parameter it is possible to vary the length of the targeted exhaust manifold and, consequently, it`s volume.

Definition of the engine operating conditions and cylinder dimensions are specified using the *EngCylinder* and *EngineCrankTrain* templates according to Table 1, as can be seen in Fig. 3 (a) and (b).



a)



b)

Figure 3: *Single-cylinder modeling by specifying a) the constructive dimensions b) the initial state conditions*

The modeling of the inlet and outlet valves respectively is done using the *ValveCamConn* template. This allows the insertion of some matrices through which the laws of motion of the valves are specified. Figure 4 shows the graphic representation of the exhaust valve lifting height according to the crankshaft rotational angle.

The *ThrottleConn* template uses the *ExhaustBrake* object shown in Fig.5 to simulate the exhaust manifold occlusion. This object simulates the existence of a butterfly valve, by which the adjustment of the gas crossing section occurs at the level of exhaust pipe. In this study, we define the parameter [DEGREE] that specified the angle of the butterfly valve from the horizontal position.

The injector was modeled by means of the *InjProfileConn* template where the type of fuel and the injection advance from TDC firing were specified. To specify the amount of fuel injected per stroke, it was chosen to define the [mgstrk] parameter, by which even the suppression of the injection may be required, as shown in Fig. 6.

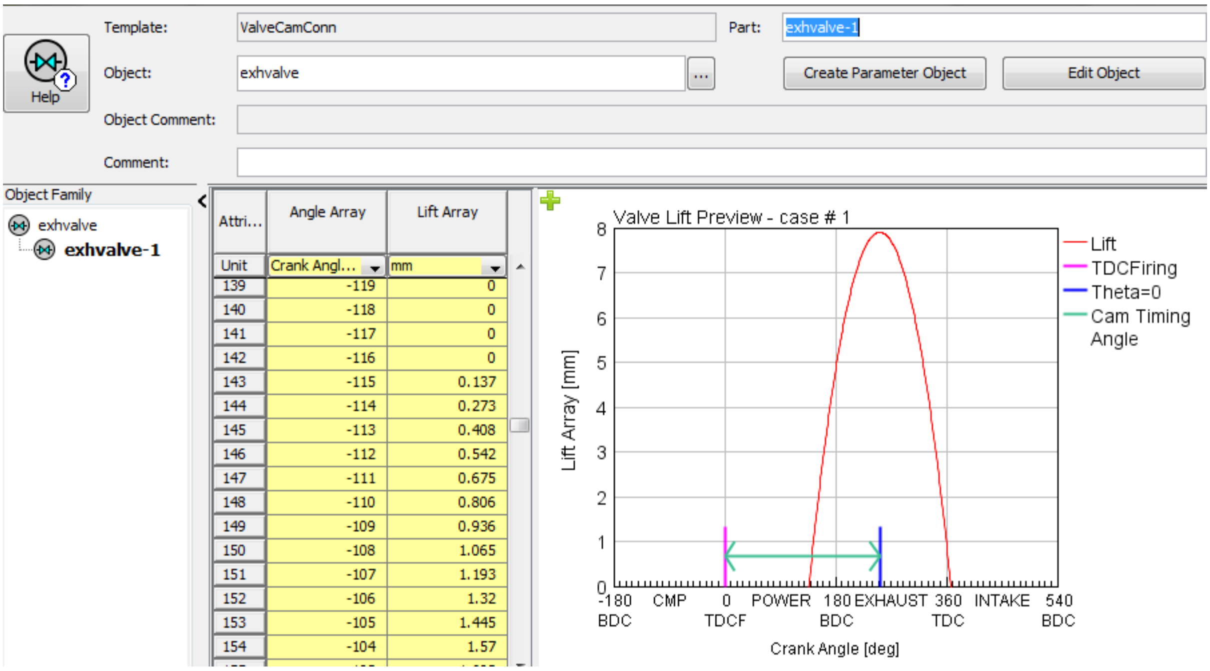


Figure 4: *Exhaust valve modeling*

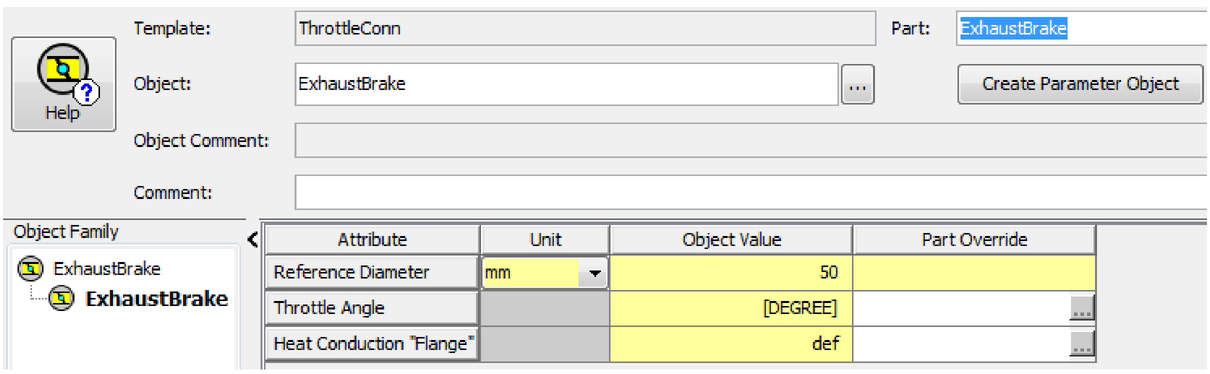


Figure 5: *Butterfly valve modeling*

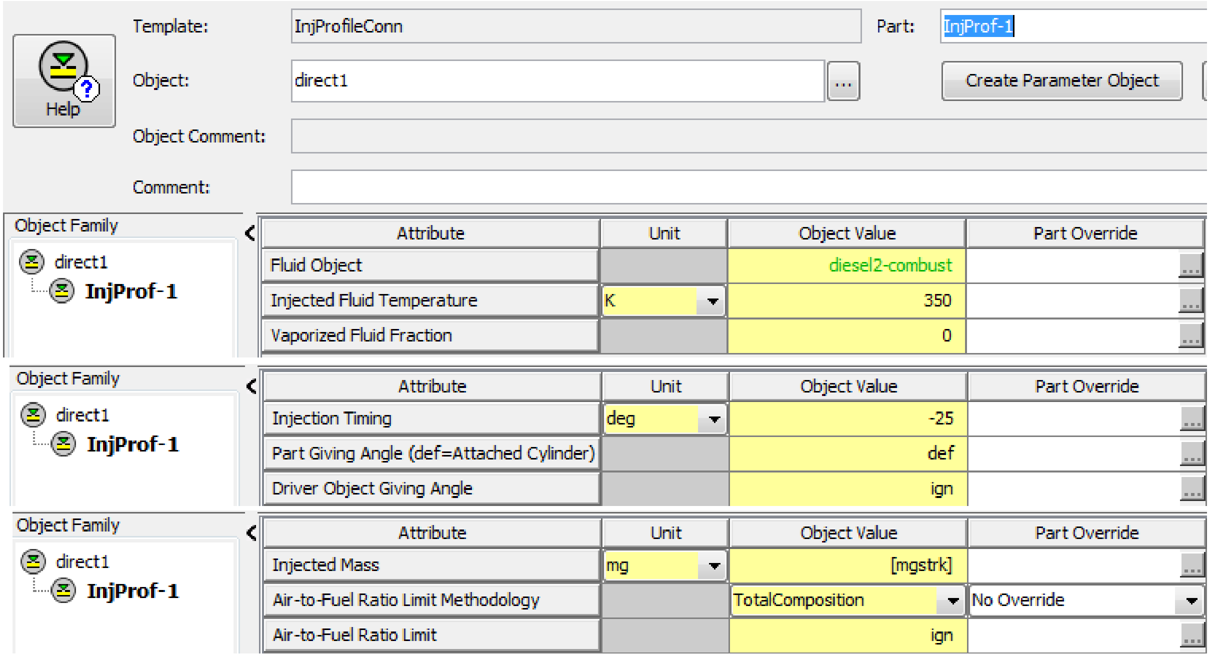


Figure 6: *Diesel injector modeling*

The GT Power software include the *Case Setup* feature, which allows to specify the value of each parameter defined previously, separately for each case of study. As can be seen in Fig. 7, five study cases were established with the same engine speed value, but the values of the other defined parameters may be changed.

The first case desire to determine the thermal-gas-dynamic parameters and the engine torque developed at the shaft of the single-cylinder engine for normal operation. The second case involves complete closing of the butterfly valve without suppressing the fuel injection. Case three involves suppression of the injection and partial closure of the butterfly valve, followed by its complete closure in the fourth case. The last case in question respects the conditions imposed in the previous case with the difference that the volume provided by the exhaust manifold segment between the valve gate and the butterfly valve is diminished by changing the parameter [L] at half. We specify that in all studied cases is assume that the engine speed is constant and equal to the engine maximum power corresponding speed.

Parameter	Unit	Description	Case 1	Case 2	Case 3	Case 4	Case 5
Case On/Off		Check Box to Turn Case On	☑	☑	☑	☑	☑
Case Label		Unique Text for Plot Legends	Combustion	Exhaust Brake 100% INJ	Exhaust Brake 30%	Exhaust Brake 100%	Exhaust Brake 100% L
mgstrk	mg	Injected mass of fuel	78	78	0	0	0
RPM	RPM	Engine Speed	3600	3600	3600	3600	3600
DEGREE		Throttle Angle	90	0	30	0	0
L	mm	Length	800	800	800	800	400

Figure 7: *Study cases setup*

3. Results

The graphic representation of the in cylinder pressure evolution is shown in Fig. 8 for three operation modes, namely: normal combustion, butterfly valve maximum shut-off with injection and without injection respectively. From the presented P-α diagram, it can be seen that in the case of normal operation with combustion , the maximum value of the in cylinder pressure reaches 134 bar and also that although the engine works with combustion but under the action of a butterfly valve fully closed, the pressure peak records an significant decrease hovering around the value of 118 bar. Moreover, during the evacuation process, which involves raising the exhaust valve from the socket and with butterfly valve fully closed, the value of in cylinder pressure increases even more significantly that the in cylinder pressure value during the combustion process has a higher value. When the fuel injection it is inhibited, the maximum value from cylinder pressure suddenly drops, being recorded only 47 bars. Theoretically, with this value would results a low mechanical stress on the engine components, what is desirable. For both cases where the exhaust brake is applied, pressure peak attenuation is observed due to the presence of residual burning gases in engine cylinder which do not allow complete fuel combustion and reduce the burning rate. Also, in Fig. 8, in the case of the engine operation in the braking mode with injection, an increase of the burning rate up to TDCF is observed as a result of the high temperature values of the residual gases in the cylinder but also one decrease in the maximum pressure value as proof of decrease cylinder filling degree with fresh gases.

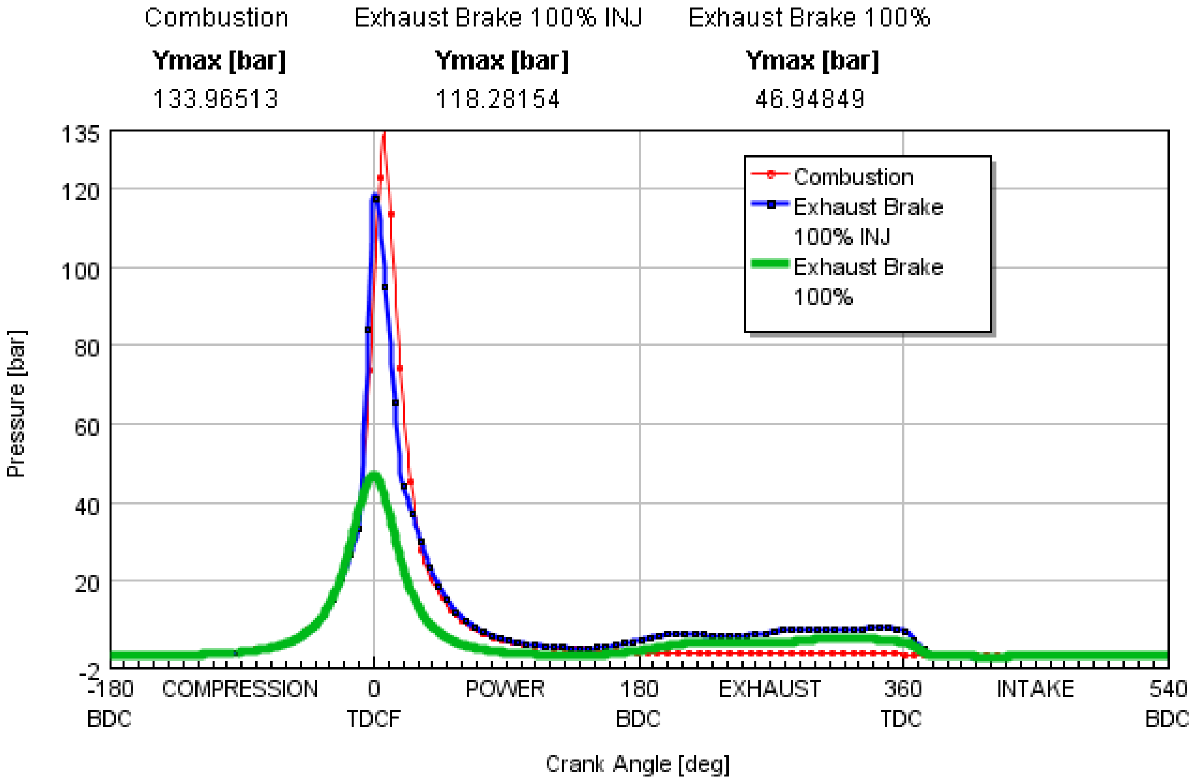


Figure 8: *In cylinder pressure evolution*

The diameter of the exhaust pipe provided for gases discharge is according with butterfly valve angle value for the five study cases and they are graphically represented in Fig. 9. Thus for the fully open position it has a value approximately equal to the diameter of the exhaust pipe, while for the fully closed position the value of the diameter provided is nonzero.

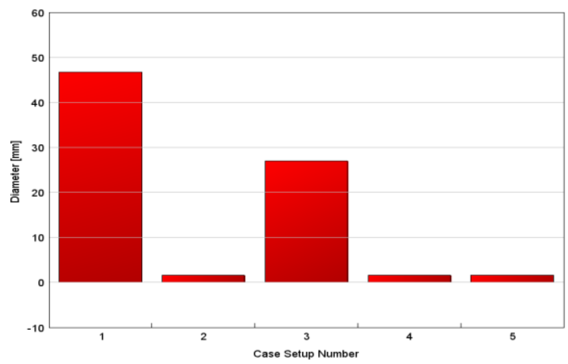


Figure 9: *The diameter of the exhaust pipe*

From this graph, it can be seen that the diameter of the exhaust pipe provided for the partial closure of the butterfly valve at an angle of 30 degrees to the horizontal position is about 27mm.

Figure 10 shows the evolution of the engine torque depending on the crankshaft angle. This representation is accompanied by the mean values of the engine torque obtained for each study case at the top. Thus the average engine torque value achieved in the case of normal combustion is 15,75Nm, value which by applying Eq. 1 lead to an engine power of 8.01 hp for imposed speed, which confirms the good accuracy of the simulation model and results.

$$P[\mathrm{hp}] = T[\mathrm{Nm}] \cdot \omega[\mathrm{rpm}] \cdot 1.424 \cdot 10^{-4} \qquad (1)$$

Where: P represents the engine power, T represents the engine torque and ω represents the engine speed.

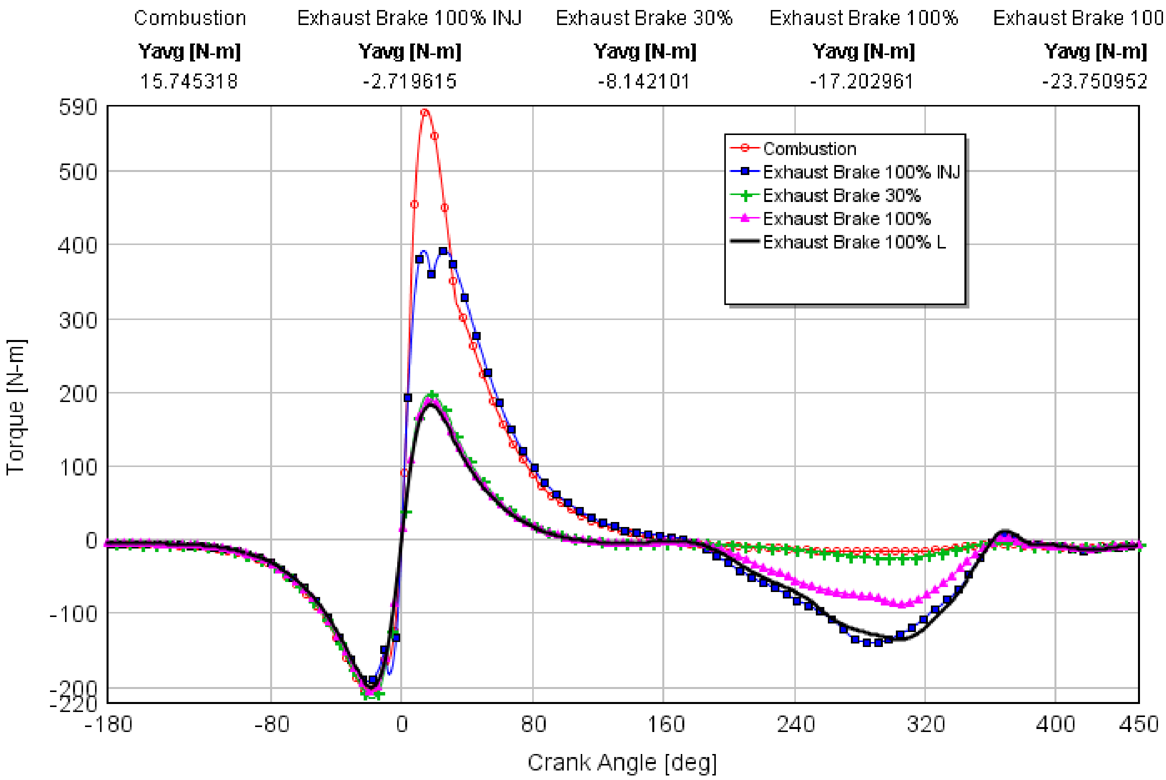


Figure 10: *Evolution of engine torque*

According to the diagram of Figure 10, it is noted that the engine torque becomes resistant torque at crank shaft by complete closure of the butterfly valve even with fuel injection, that lead to a kinetic energy loss reducing in this way the travel speed of the vehicle.

In the case of fuel injection suppression, it is noted that the value of the resistant engine torque has a substantial increase and directly proportional to the degree of obstruction of the exhaust manifold section, reaching the value of -17.2 Nm in case of complete closure of a butterfly valve to Lombardini 6LD400 engine.

In the latter studied case, which takes into account the decrease of the volume of the exhaust manifold between the gate of exhaust valve and the butterfly valve indicates that the resistance moment value at the crankshaft is strongly influenced by the volume where the engine cylinder gases expansion occurs at the lifting up of exhaust valve from the socket. In these conditions, the engine torque has an increase of 50 percent compared to the previously studied case when the increase was only 10 percent higher than the crankshaft engine torque in the case of combustion operation.

4. Conclusions

The engine torque value is closely related to the in cylinder pressure evolution over an entire engine cycle that operates in the exhaust brake mode.

According to the obtained results from this simulation, the theoretical braking power that can be developed by installing an exhaust braking system can in some cases exceed the nominal power achieved in combustion mode on a single-cylinder engine.

Although, in the second study case the fuel injection is not suppressed, it is noted that by obstruction of the exhaust manifold shows up a torque resistant at the engine crankshaft which can be used to reduce the vehicle travel speed. In other words, the exhaust brake system can be used with or without suppression of the fuel injection. But the study shows that the effectiveness of this braking systems type varies inversely with flow section offered to the exhaust gas by the exhaust manifold, a higher efficiency is obtained for a complete closure of the butterfly valve and the fuel injection suppression.

The results show that with the suppression of the injection at the beginning of into operation of an exhaust brake system, a reduction of mechanical stresses at the level of the engine cylinder components it takes place, but a thorough study is needed on the forces that acts at the crankshaft and the transmission.

As shown by Fig. 10, the evolution of the engine torque when is used an auxiliary brake system of the exhaust type while the fuel injection running, the engine torque value exhibits sudden variations that leading to mechanical fatigue stress shortening the lifetime engine.

From the latter study case, we can conclude that the volume of the exhaust manifold provided for expanding the cylinder gases, when engine operating in the exhaust brake mode, is an important parameter which can easily lead to an significant increase in torque resistant over 150%, relative to the torque developed by the engine in case of combustion operation mode.

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