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TEST VALIDATED 0D/1D ENGINE MODEL OF A SWINGING VALVE INTERNAL COMBUSTION ENGINE

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Abstract

In the quest for reaching ever higher power density of IC engines a much simpler solution has been investigated that allows vehicles to reach a comparable power level with cars equipped with turbo charged engines. The new Swinging Valve (SwV) arrangement enables the unhindered gas exchange process through an engine. In this experiment a flow bench was used to examine a normal poppet valve cylinder head and a cylinder head constructed for the same engine but with Swinging Valves. The flow parameters of the original cylinder head were obtained then the SwV head was investigated in the same way. To examine the practical use of a SwV system a 0D/1D engine simulation had been created, first using the engine with conventional cylinder head. That model had been validated with dynamometer tests. After this stage the results of the Swinging Valve flow measurements were fed in the same 0D/1D engine simulation then the results were compared and examined.

***Keywords**: IC engine, Swinging Valve, Poppet valve, flow test, 0D/1D engine simulation*

1. Introduction

Even to date, internal combustion engines use poppet valve systems with varying degree of system complexity. Due to their general shape and arrangement poppet valves seal the combustion chamber quite effectively. While doing so they, unfortunately, obstruct flow to and from the cylinder creating substantial losses during the gas exchange process. Another problematic area is the retaining spring with the mass moving together with the valve. This creates an oscillating system that will resonate at certain engine speeds requiring special attention during the design of the cam shaft and cam lobe shape. (Kovács, 2014)

To overcome all of these problems the employment of Swinging Valves (Fig.1) is proposed. Applying this system flow parameters can be greatly improved facilitating that engine downsizing in general can be done more efficiently and cheaper (Kovács and Szabó, 2013).

2. Materials and methods

2.1. Test engine

To validate the results of the Swinging Valve project a Suzuki SV650 motorcycle engine had been chosen. For recording the engine parameters, a rolling road dynamometer was used. The actual measurements were conducted on a Superflow CycleDyn Pro (SF-250)- WynDyn 3.2 dynamometer. On the test bed the vehicle's air intake openings are supplied with air at a speed that would exactly match to the road speed of the tested vehicle. This reproduces the actual road conditions and increases the accuracy of the test. The actual engine data can be found in Kovács and Szabó (2015) while Fig. 2 presents the torque and power curves obtained on the rolling road dynamometer.

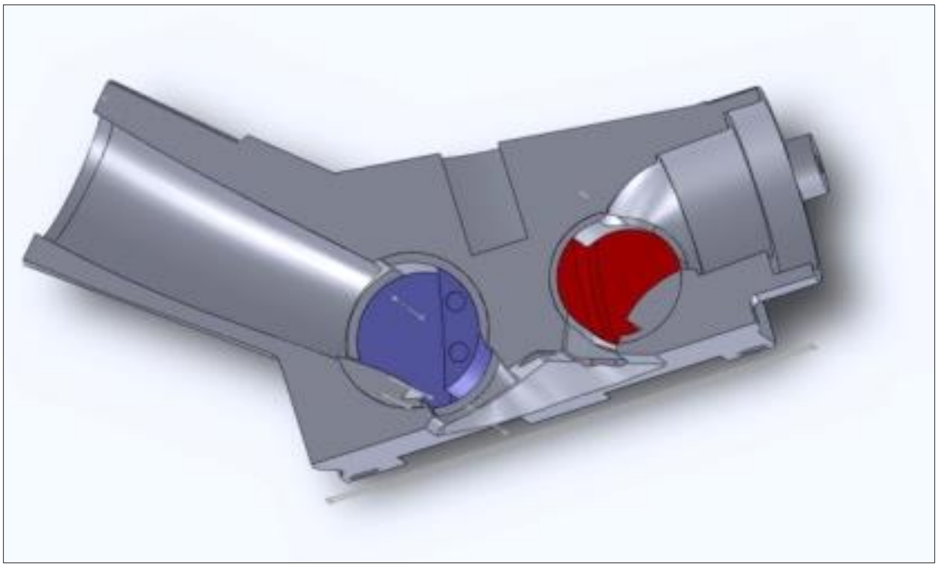

Figure 1. *Swinging Valve cylinder head section view.*

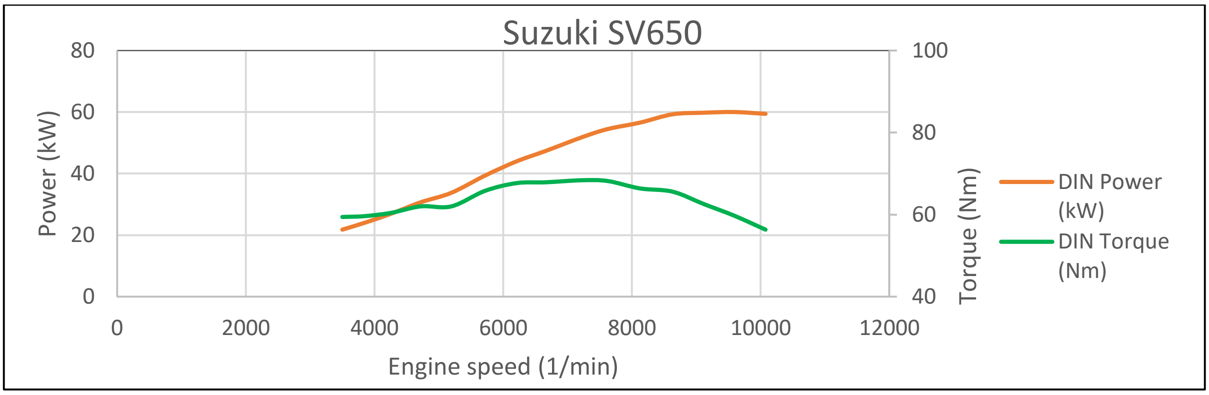

Figure 2. *Torque and power curves of the Suzuki SV650 test engine as measured on a SuperFlow CycleDyn dynamometer.*

To create a baseline for the examination of the Swinging Valve the original poppet valve cylinder head's flow capability was measured. A SuperFlow SF600 steady state flow bench was used that is designed to measure the air-flow resistance of intake and exhaust conduits of internal combustion engines. The flow measurements were taken at different valve lifts. The test methods, the actual test and the specifications of the test equipment are presented in the work of Kovács and Szabó (2019).

2.2. Test considerations with the Swinging Valve arrangement

At the lift points, where measurements were taken with the poppet valve cylinder head (Kovács and Szabó, 2019), the nominal flow area values were calculated. To test the Swinging Valve head the valve were set in those positions where the valve opening had the exact same nominal flow area value of the poppet valve head at a given lift point (Fig. 3). This way the results could be directly compared and plotted in common graphs for both valve types. The tests were conducted according to the methodologies prescribed by SuperFlow (2010). At each lift point the flow was recorded in cubic feet per second and then converted to ISO unit m^3/s.

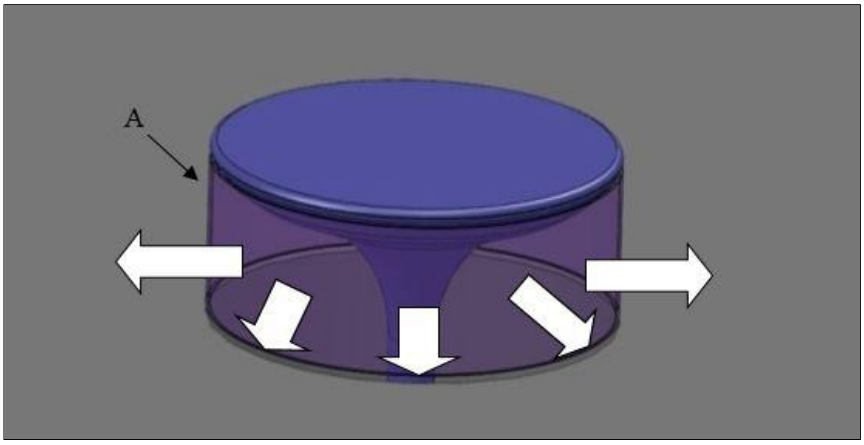

Figure 3. *Nominal flow area of a poppet valve. The white arrows show the assumed particle flow trajectories (Kovács and Szabó, 2019).*

3. Comparative results of the flow test

3.1. Direct flow measurement

As stated by Kalmár and Stukovszky (1998) an intake system that is more efficient in terms of flow losses is favourable as the volumetric efficiency and specific fuel consumption is improved. As Kovács and Szabó (2019) states: "*With better flow characteristics the spread of torque and exhaust gas emissions are also improved. In the light of engine downsizing efforts this translates in to smaller engines with the same characteristics and driver perception that a larger, heavier engine would provide with higher fuel consumption.*"

Both cylinder heads equipped with the different valve systems were tested with a flow smoothing adapter. The obtained volumetric flow data is displayed in Fig. 4.

As can be observed the Swinging Valve's flow capacity is greater than that of the poppet valve system. The obtained graph for the exhaust Swinging Valve shows some erratic behaviour along its path that indicates irregularities in the flow field. This may be caused by the turbulences around the edges of the exhaust SwV. In the intake port the flow is smooth without disturbances and reaches its maximum at 0.08 m^3/sec.

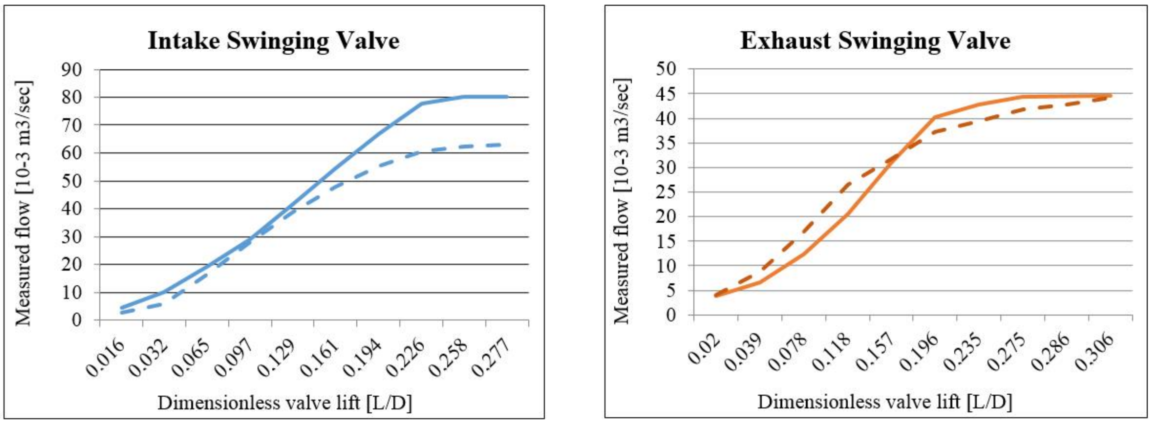

Figure 4. *Graphical representations of measured flow parameters of the intake and exhaust Swinging Valves. For comparison, flow values of the original poppet valves are also shown with dashed lines (Kovács and Szabó, 2019).*

3.2. Further data processing for 0D/1D engine simulation

As volumetric flow data cannot be entered directly into 0D/1D engine simulations the Coefficient of Discharge (*Cd*) for both valve systems were obtained. This dimensionless quantity indicates the actual rate of contraction of the flow past the valve openings. In the case of poppet valves the real flow area is conical and this feature is taken into account and is embedded in the calculation procedure as described by Gault et al. (2004) (Fig.5).

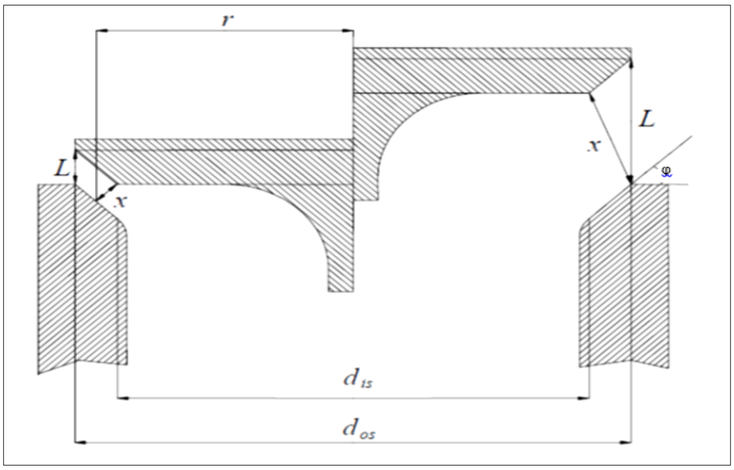

Figure 5. Graphical representation of the shape and position of the flow area (Gault et al., 2004).

Using the equations between valve and valve seat that were presented in the work of Kovács and Szabó (2019), *Cd* can be determined as the ratio between the actual conical valve flow area and the theoretical valve flow area at each valve lift point. According to the theory presented by Dezsényi et al. (1992) dividing the volumetric flow rate values by the flow speed we obtain the actual flow area, and from that the Coefficient of Discharge is calculated as follows:

$$Cd = \frac{\dot{V}_{ac}}{A_t \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}}}, \tag{1}$$

where:

$\dot{V}_{ac}$: Actual volumetric flow rate [m^3/s],
A_t: Theoretical valve flow area at each valve lift point [m^2],
Δp : Pressure drop across the valve annulus [Pa],
ρ : Density of air [kg/m^3].

After completing the calculations, the following graphs were plotted for the Cd values for both the poppet valve and the Swinging Valve cylinder head *(Kovács and Szabó, 2019), (Fig. 6-7.).*

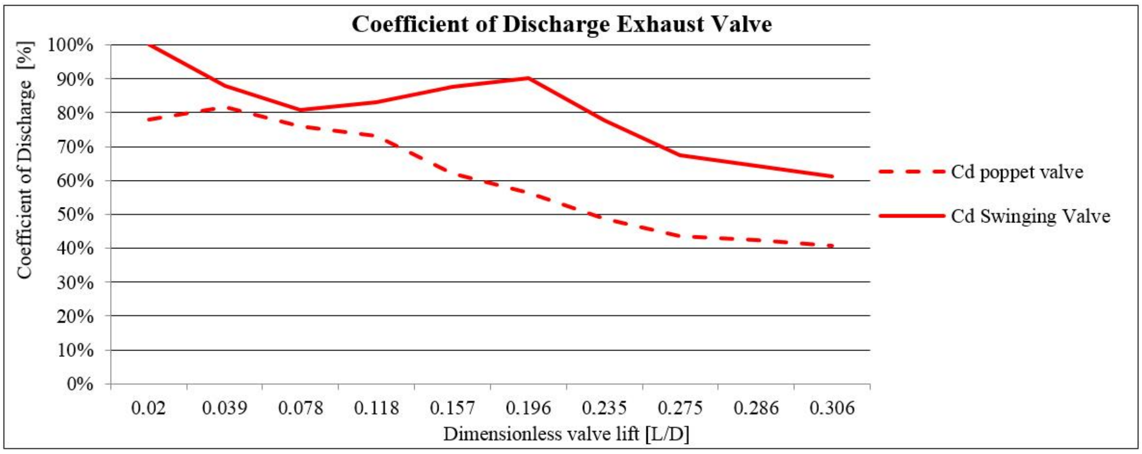

Figure 6. *Coefficient of Discharge (Cd) values for exhaust Swinging Valve. For comparison, Cd values of the original poppet valves are shown with dashed lines.*

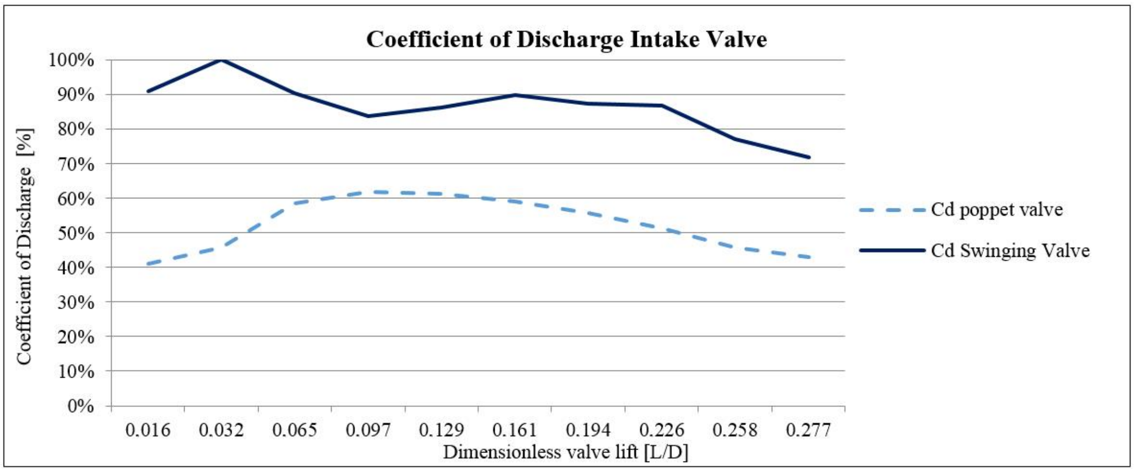

Figure 7. *Coefficient of Discharge (Cd) values for intake Swinging Valve. For comparison, Cd values of the original poppet valves are shown with dashed lines.*

4. 0D/1D engine simulation

4.1. Definition of a 0D/1D simulation

As Lopez and Nigro (2009) states: "*The modelling of reciprocating and rotary internal combustion (IC) engines is a multidisciplinary subject that involves thermodynamics, fluid mechanics, turbulence, heat transfer, combustion, chemical reactions, mathematical analysis, and numerical methods*."

Engine simulations can be classified into different categories. Most simple approaches use zero-dimensional single zone solutions while multidimensional models are used to reach the most accurate results. However their accuracy still depends on the presumed initial conditions, while their computational power requirement is also very high that prevents widespread use.

For our purposes we chose a 0D/1D model that can predict the performance of our test engine with sufficient precision whereas not requiring a costly computer background. In 0D/1D simulation, components belong to two greater groups: connection elements and devices.

Devices, such as valves, plenums, branches, etc. only have information on their thermodynamic qualities that are treated as component averaged scalar values. These components make up the 0D elements of the model. Connection elements represent the pipes and any other pathways in which air, air-fuel mixture or exhaust gas can move along. Only those equations are solved that describe charge motion parallel to the walls of these connection elements. Therefore they are named 1D elements.

As can be found in the work of Maynes et al. (2002) 0D/1D engine simulation software can be coupled to various 3D-CFD software to increase accuracy however the time needed to complete modelling is also increased.

4.2. Structure of the simulation model

The simulation model was built with components described in the previous section as a network of different elements (Fig. 8). Detailed description on building the engine model and the entire modelling process is presented by Kovács and Szabó (2015).

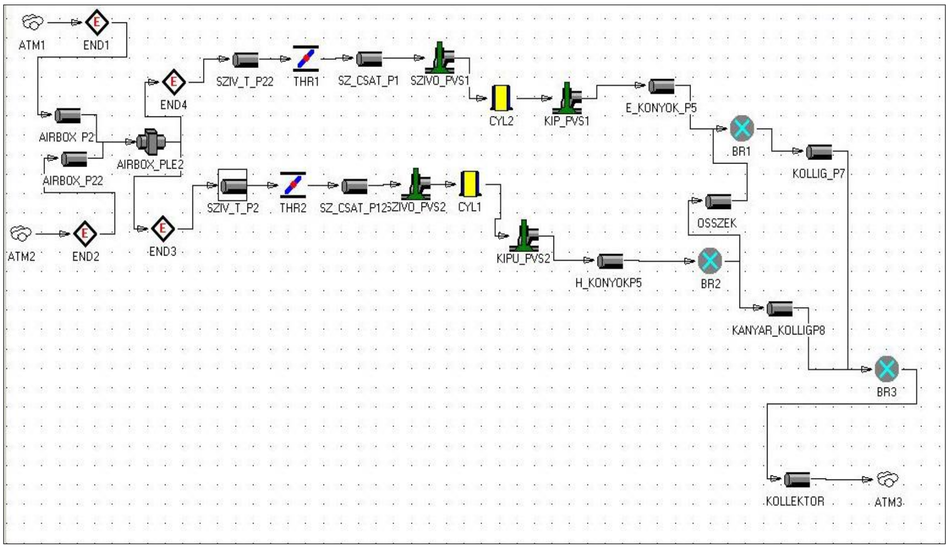

Figure 8. *Layout of engine simulation model (Kovács and Szabó, 2015).*

Our research's focal point is the examination of the difference in Coefficient of Discharge regarding poppet and Swinging Valve systems. Therefore the data obtained by flow bench tests, and was presented in Section 3, had been further processed. The highest pressure ratio in our tests, across the examined valve systems, was 1.1 but as Blair et al (2001) states the actual pressure ratios in a running engine are much higher. To account for the change of *Cd* as a function of pressure ratio, *Cd* values calculated up to a pressure ratio of 2 by using the extrapolation function of the simulation software (Optimum, 2003). The returned result was a surface of *Cd* values as a function of relative valve lift and pressure ratio. Since the pressure fluctuations during the gas exchange process do revert the flow direction in certain engine speed ranges and piston positions *Cd* values were calculated for the reverse flow conditions for the examined valve systems (Kovács and Szabó, 2015).

5. Results of modelling

After setting up the model using the poppet valve cylinder head's test data (valve opening and closing points, *Cd* values, etc.) the software was started and after a few runs produced acceptable results that matched the measured power and torque characteristics of the engine quite well. After manipulating otherwise non-measurable parameters such as cylinder wall temperature, etc. subsequent runs resulted in a further refined model that reached a maximum average model error of 3% between simulation and dynamometer measurement of engine power, while it was 4% in the torque characteristics (Fig. 9-10). This surpassed the average model error target of 5%, which value is considered to be of sufficient precision (Gurney, 2001).

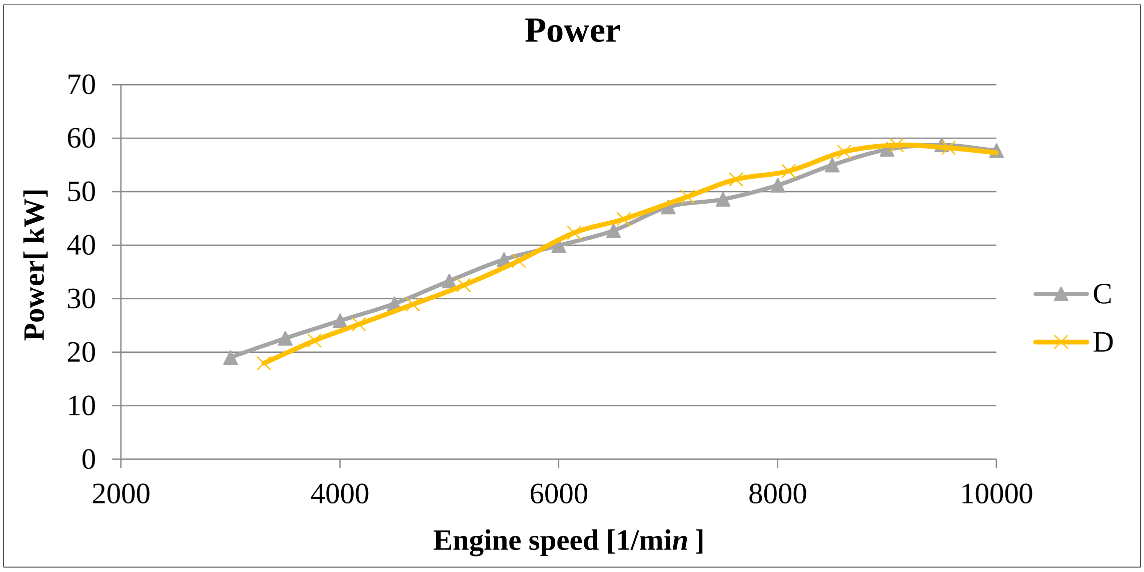

Figure 9. *Comparison of measured and simulated power output of the test engine. C: Simulation D: Measurement.*

In the torque curves it can be clearly seen that general trends, troughs, etc. occur at the same engine speed in the model as in the measurements. The reason for the differences seen in the lower half of the engine speed range is caused by the rich air-fuel mixture produced by the OEM Engine Control Unit of the dynamometer tested engine.

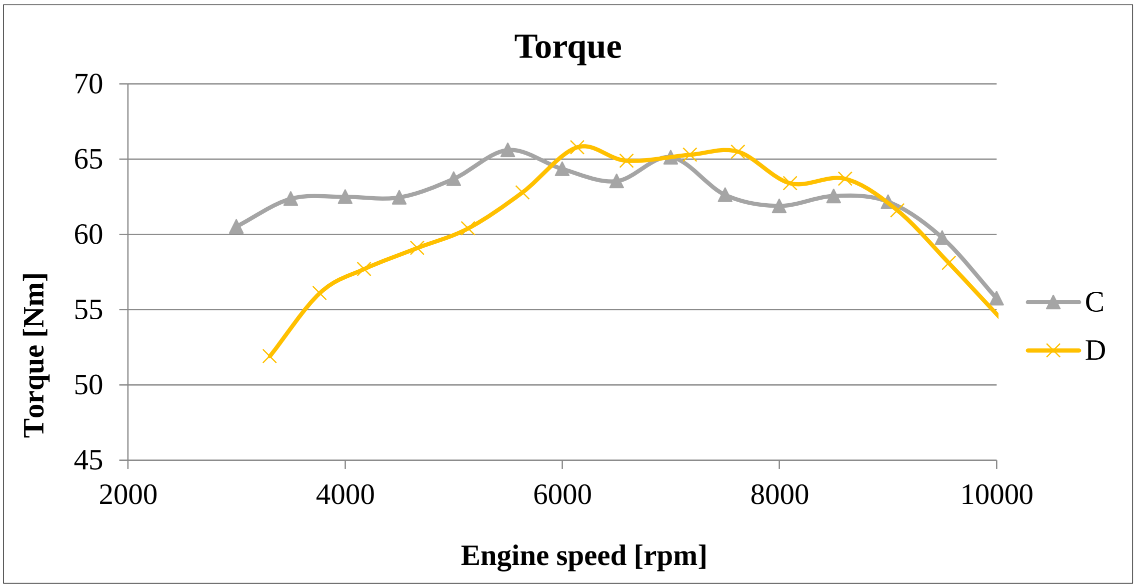

Figure 10. *Comparison of torque characteristics of simulations and measurement. C: Simulation D: Measurement.*

6. Incorporating swinging valve in the 0d/1d engine model

Since an acceptable result was produced with the poppet valve cylinder head simulation, thus the simulation had been verified, the same platform could be used in the final part of the project.

As a next step the *Cd* values of the poppet valve system were replaced by the results from the Swinging Valve cylinder head flow tests while valve lift profiles and valve opening and closing points were kept unchanged: same as with the poppet valves.

In order to pinpoint the differences and possible benefits between the two valve constructions the results of the SwV simulation runs were evaluated against the simulation results of the poppet valve head equipped engine.

6.1. Comparative assessment of simulation results based on different valve constructions

6.1.1. Torque

Since equivalent lift and valve timing figures were used the difference between the results can only be produced by the different flow capabilities of the valve concepts. As can be seen in Fig. 11. at high engine speeds Swinging Valve system gives superior torque due to its better flow characteristics. At lower speeds it is also performs better while between 5000 and 6500 1/min it gives equal torque figures to the poppet valve cylinder head. The only deficiency is shown between 4000-5000 1/min where the Swinging Valve’s better flow characteristics gives way a greater amount of backflow from the cylinder. This results in lower filling of the cylinders decreasing the torque available in that speed range. Otherwise the motive force generated by the Swinging Valve equipped engine is higher than the original poppet valve engine.

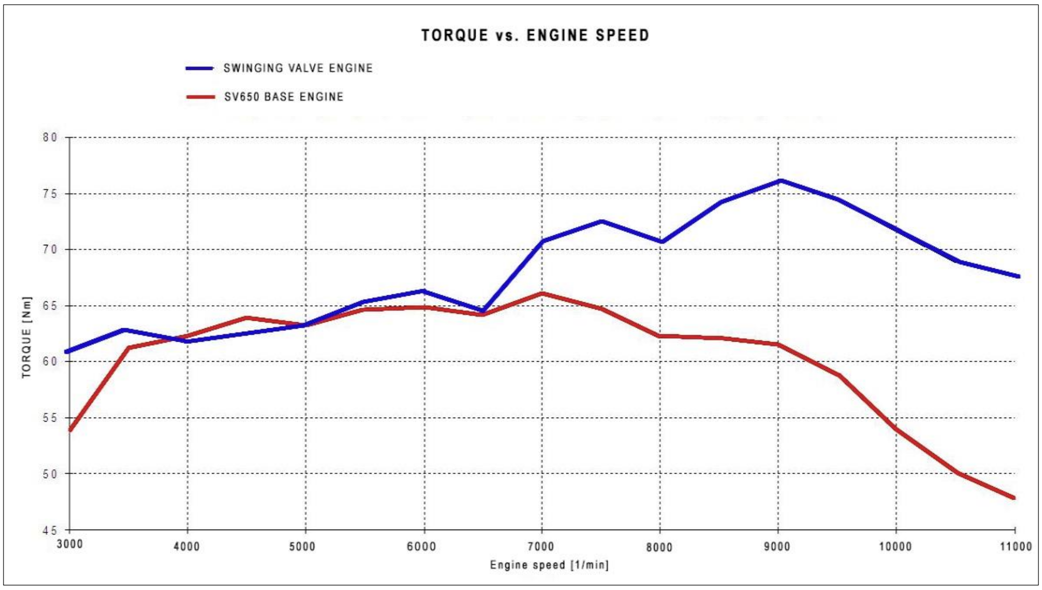

Figure 11. *Simulated torque characteristics of the poppet valve SV650 base engine and Swinging Valve engine.*

6.1.2. Power

The differences in the power curves (Fig. 12) caused by the dissimilar flow characteristics are masked somewhat by the engine speed that plays a significant role in calculating power figures. To assess the performance of the Swinging Valve cylinder head engine the Delivery Ratio plots can present a better platform for further analysis.

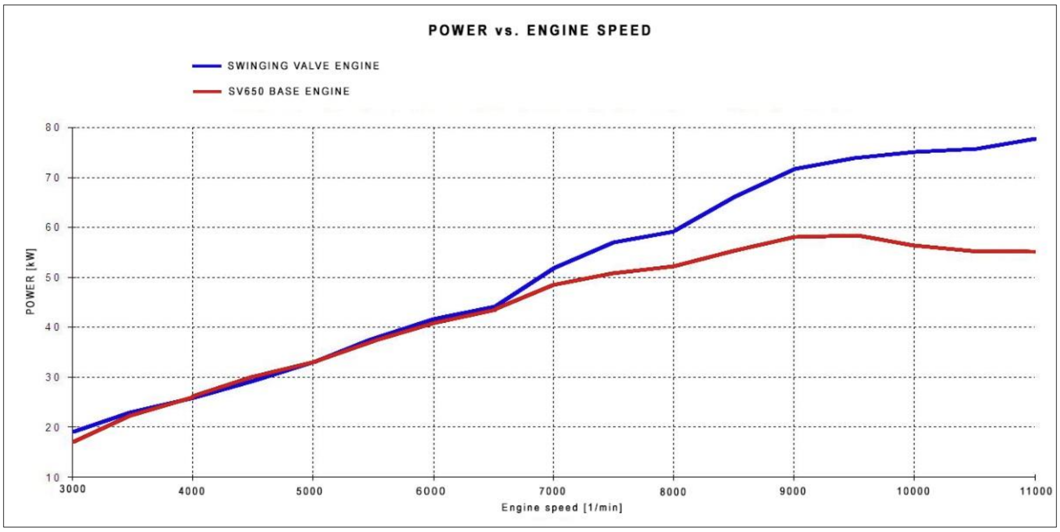

Figure 12. *Simulated power characteristics of the poppet valve SV650 base engine and Swinging Valve engine.*

6.1.3. Delivery Ratio

By definition Delivery Ratio (DR) is the specific mass airflow rate into the engine (Blair, 1999). It is calculated independent of engine swept volume and engine speed hence it is more useful to judge the performance of the SwV system. As can be seen in Fig. 13, DR is higher almost in the entire rpm range except between 4500 and 5000 1/min's. It can be observed that in this range DR reaches 92% then at 6500 1/min again 95%. A marked decrease in DR can also be seen at 8000 1/min.

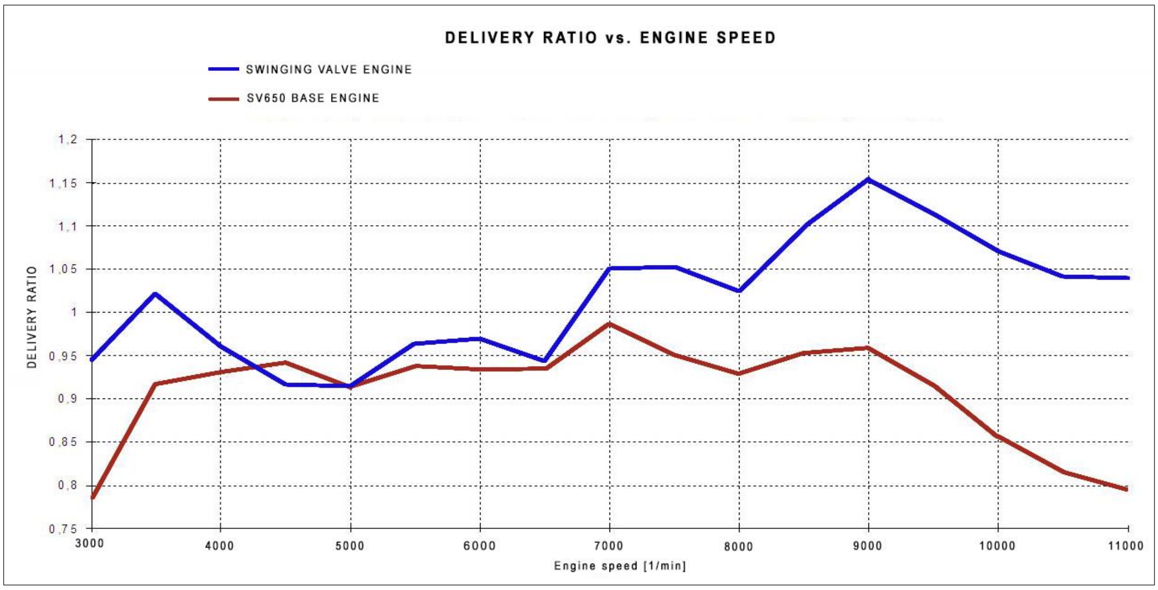

Figure 13. *Simulated Delivery Ratio characteristics of poppet valve SV650 base engine and Swinging Valve engine.*

The peaks and troughs are the result of pressure waves acting in the engine manifolds improving and deteriorating cylinder filling at the mentioned speeds. The real problem with this situation is that it is compounded by the resonance effects of the exhaust pipe that is superimposed on the wave action in the intake manifold. A probable example to this is the dip at 6500 1/min. The situation above 10000 1/min is similar in both cases presumably because the net flow areas become the limiting factor.

7. Conclusions

During the course of the Swinging Valve project a number of interconnected areas were examined. All the findings in the experimental stage were validated against measured parameters before the Swinging Valve concept was put to test. As has been shown it was not necessary to know the exact 3D fluid dynamics in an engine or in its subsystems to produce a model with sufficient accuracy. The method presented demonstrates the possibilities that help the designer to track down the gas dynamic phenomenon in a running engine.

With the introduced Swinging Valve concept an engine's pumping losses can be decreased, the cylinder filling could be improved hence not requiring additional fuel or auxiliary devices, such as turbo chargers to reach the improvements in engine parameters. These beneficial effects have been clearly demonstrated in improved Power, Torque and Delivery Ratio in 0D/1D engine simulation.

It has been proved that Swinging Valves present less obstruction to flow and that clearly appears in their higher mass flow rates at maximum opening than the poppet valve system.

Therefore it can be concluded that the results of the investigation of Swinging Valves are well justified. As a final conclusion and a result of this present research work, the idea of having a non-conventional Swinging Valve arrangement has been proved to be superior in a number of fields to the original poppet valve system of the test engine.

8. Acknowledgements

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