

MUSIC Technology Overview

Powertrain Technologies Ltd

Summary

The MUSIC technology is a novel throttle less engine allowing ultra-lean burn leading to significant improvements in thermal efficiency and thus enhanced fuel economy and reduced CO₂ emissions. It has been under development in single cylinder form at Coventry University in the UK for the past 5 years and has just completed a project, part funded by the UK Government, to produce a 4 cylinder demonstrator engine. This engine successfully achieved a 19.8% improvement in fuel economy over the project baseline engine, a Ford 2.0lt port injected Duratec, on a simulated European drive cycle.

Over and above the CO₂ reduction MUSIC also offers very considerable reductions in NO_x and HC emissions. Whilst at this stage the HC benefits are theoretical due to a lack of suitable injection equipment, the NO_x benefits were observed with dramatically reduced raw NO_x output..

The technology is based on the use of a separate combustion chamber into which the majority of the air mass is transferred. Fuel is injected into one end of the chamber and the spark plug is located at the opposite end. The chamber is a simple plain cylinder designed to allow for fully controlled air motion and thus managed stratification of the fuel and air. The air motion is controlled by means of a design feature at the point where the air enters the chamber. This allows for a stoichiometric mixture to be held around the spark plug whilst the mixture in the rest of the chamber can be lean or even have no fuel at all depending on the required load on the engine. The engine can run at global air fuel ratios up to 100:1 (idle condition). This results in dramatic reductions in combustion temperatures and, coupled with a reduced surface area, a very significant reduction in heat loss.

The 4 cylinder engine does require a new cylinder head however the rest of the engine uses standard production parts. The use of an existing production bottom end plus the need for the engine to function as a research engine with considerable flexibility in the design of key components and the addition of considerable instrumentation posed significant constraints on the design. The most significant manifestation of these constraints is the use of only 2 valves vs the original 4 valves. It is anticipated that a head designed for production would be a 3 valve unit.

A critical element in the new technology is the injection system. In order for the technology to work it is a requirement that injectors with the correct spray characteristics are used (cone angle and flow rate) plus the ability to provide multiple pulses on each cycle. These requirements are simple variations on existing production parts (in terms of angle and flow), and the operating pressure does not need to exceed the current gdi norm of 120bar.

In order to secure the correct injectors it was important that the assistance of a fuel system supplier was secured. Unfortunately the project was unable to secure such assistance from any of the major fuel system suppliers and thus was not able to procure suitable injectors. This resulted in the project being forced to search for and use off-the-shelf injectors which were closest to our requirements. Whilst injectors for the 4 cylinder engine were eventually found that were at least close enough to the requirement to be useable, they still had both an incorrect spray angle and a flow rate nearly twice that required.

The results of the 4 cylinder test were nonetheless highly successful with the engine demonstrating a 19.8% economy improvement on a calculated NEDC test cycle against a 20% target. The results are based on a Ford proprietary test sequence which allows for dyno test data to be converted to a vehicle drive cycle and thus a vehicle economy figure to be computed.

Technology Description

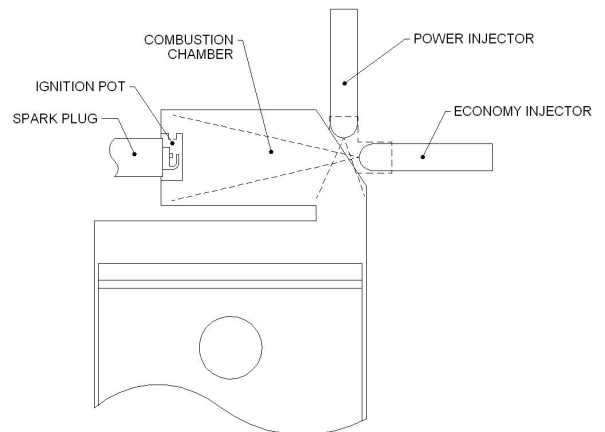
In a conventional engine the thermal efficiency is compromised by the loss of heat from the cylinder during combustion plus the pumping losses incurred when the engine is heavily throttled at part loads. MUSIC overcomes the pumping losses by running completely un-throttled at all loads. MUSIC dramatically improves on the heat loss by two means. Firstly at loads up to 70% the combustion takes place in a separate chamber, this has a lower surface area than the main cylinder and thus reduces the

heat loss. Secondly the engine runs ultra lean. Thus at light loads for instance, up to 90% of the cylinder contents are at compression temperature only, leading to bulk temperature dilution and thus significantly reduced heat loss. The combination of lower temperature and lower surface area means that at 10% load the heat loss is less than 4% of that suffered by a conventional engine.

Unlike other future technologies (such as HCCI/CAI) MUSIC does not need any new support technology or complex support systems. All the gains are achieved by the re-arrangement of the combustion process into a separate chamber and the use of currently available gdi fuel systems. There is a generally accepted model that reductions in CO₂ have an associated technology on-cost. This increase in piece cost can be anywhere from \$150 to \$250 to achieve a 5% reduction in CO₂. MUSIC disrupts this paradigm. The 4 cylinder engine produced during this project has a maximum projected on cost against the port injected base line of just \$50 yet it produces a 20% benefit. This is a cost/benefit of just \$2.50 per percentage point improvement in CO₂ emissions vs a best figure of \$30 per point with existing engine technology. Since the technology also has considerable emissions advantages beyond just CO₂ there may be further cost advantages in a reduced after treatment requirement.

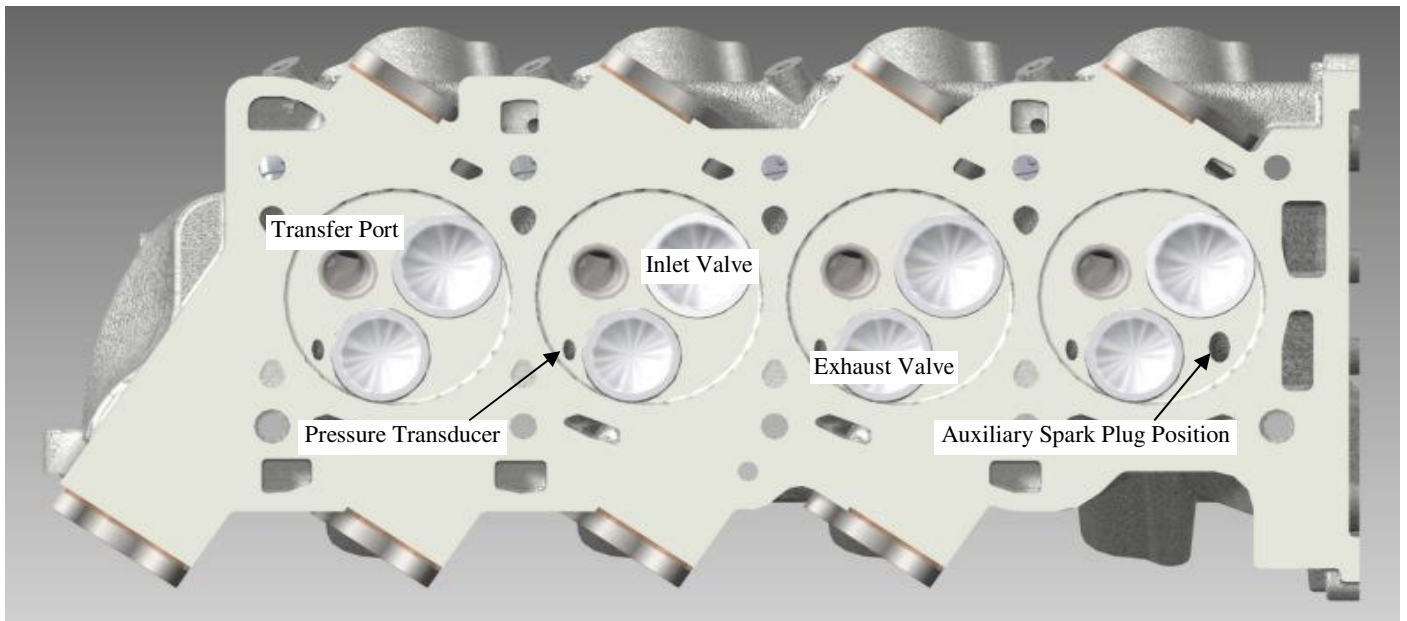
Combustion System Layout

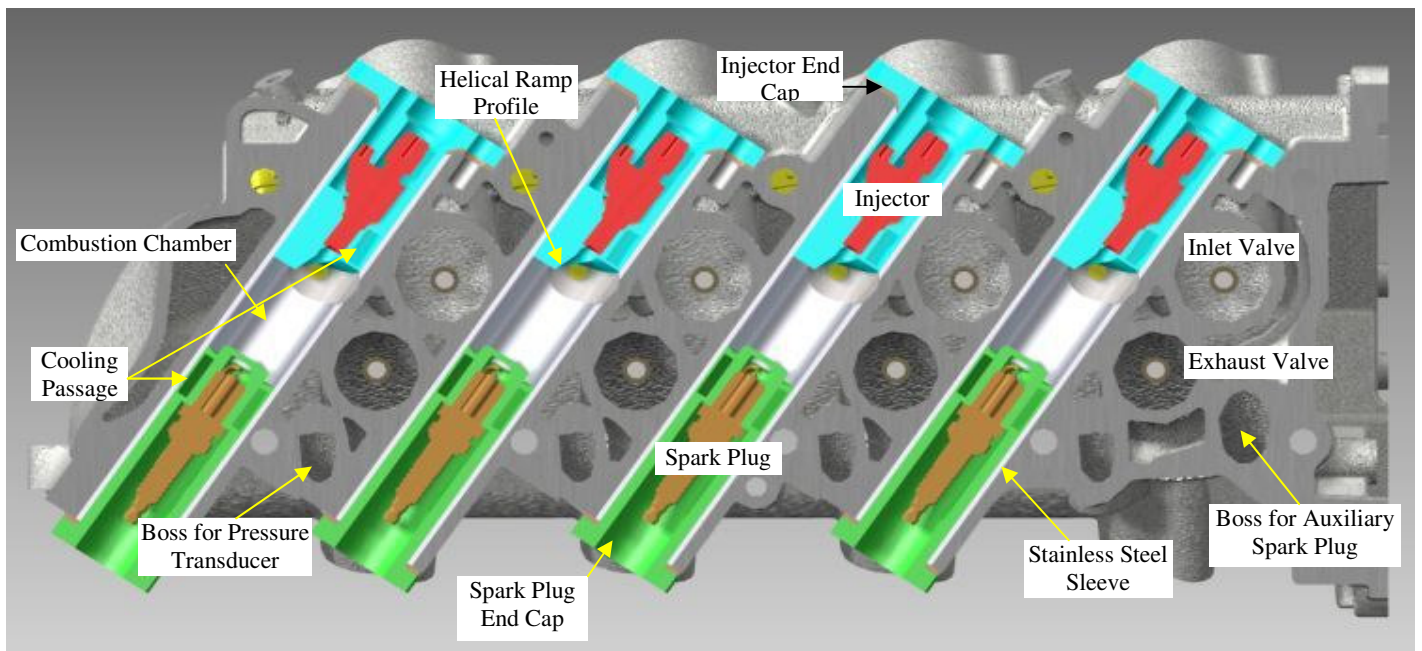
The sketch alongside shows the layout of the MUSIC combustion system. At this stage the sketch shows the provision for 2 injectors. This layout was derived to overcome the lack of support from an FIE system supplier. The consequence of this design is to provide considerable flexibility in the supply and timing of the fuel, although it still requires that the injectors themselves have the desired configuration. This layout is therefore well suited to the needs of a development system.



Schematic diagram showing key component locations

The two images below show the layout of the cylinder head as viewed from the fire face. The first image is the complete head to give an image of the positioning of the major components whilst the second image is a cutaway view showing the components in situ.





In viewing the two above layouts it is very important to bear in kind that the head is designed as a development tool with a need to incorporate provision for instrumentation requirements plus allow for the two ends of the combustion chamber to be removable for design modifications. The helical feature which controls the air motion within the chamber is clearly visible on the end of the blue end cap. Also included in #1 cylinder is provision for an auxiliary spark plug for research purposes.

The result is a heavily compromised layout. A production head is expected to have the chamber as a cast feature and the overall design to be very greatly simplified which would result in a much easier package allowing a third valve to be included.

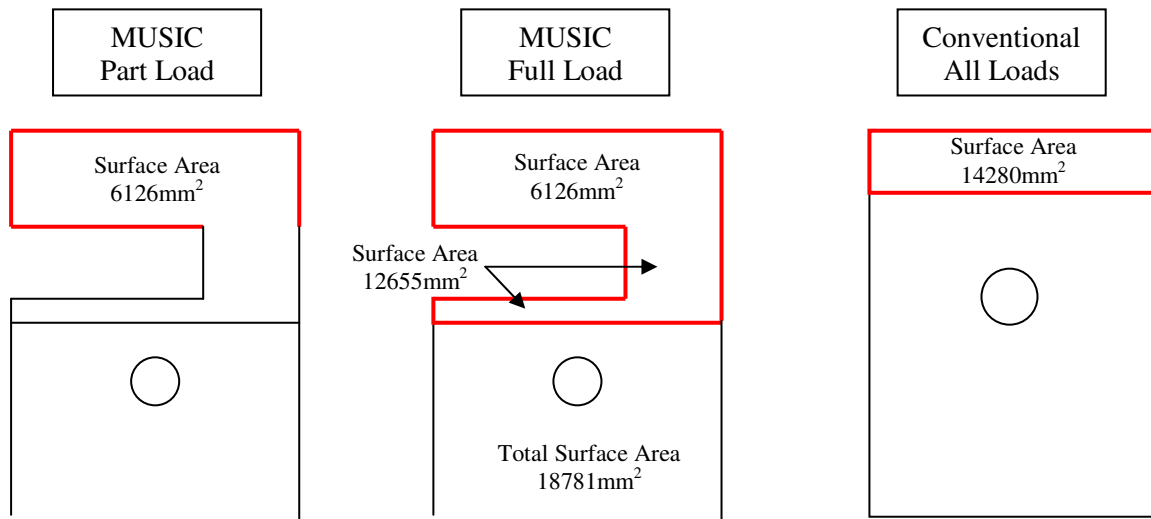
Emissions Potential

The technology has very great potential for emissions reductions over and above the target CO₂ reduction. Due to the geometry of the chamber the crevice volumes are greatly reduced and with an accurate injector spray pattern it is anticipated that HC emissions may be reduced by as much as 50% over the base engine. Unfortunately due to the lack of an optimised injector it is not possible to evaluate this feature as both the spray pattern and flow rate used in the tests are away from optimum and thus result in higher HC's.

NO_x emissions are also of great significance as they are a critical emission generally requiring expensive and complex after-treatment. Current expectation is that over the NEDC drive cycle the NO_x emissions may be reduced by up to 85% and over the whole engine operating range they may be down by an average of 40%-50% depending on drive cycle. This estimate is based on the AFRs required over the drive cycle which (apart for the extra urban stage) are no richer than 50:1. Test bed work shows that raw NO_x at these AFR's are up to 10 times lower than a conventional throttled engine. Even above this level NO_x output is heavily suppressed until AFR's reach the low 30's when they begin to climb as might be expected in what is a fairly well understood region of engine operation.

Heat Loss Calculations

A critical feature of the technology is the reduction in heat loss achieved by virtue both of the lean burn and the use of a separate chamber. The use of the separate chamber reduces the surface area through which heat can escape during part load operation. The sketches below compare the surface areas of the MUSIC engine to a conventional engine.



The three sketches above show how the surface area of the MUSIC system compares to a conventional engine at TDC. Due to practical considerations such as production tolerances, valve clearances etc. it is not possible for 100% of the combustion air to be pushed into the combustion chamber. The maximum proportion of the available air that could sensibly be moved into the chamber is 72%. The remaining 28% is in the area above the piston and in the transfer port.

	MUSIC			Conventional Engine
	Combustion Chamber	Area above piston	Total	
Diameter	30mm	87.5mm		87.5mm
Length	50mm	2.3mm		8.2mm
Area of each end face	707mm ²	6,013mm ²		6,013mm ²
Area of cylinder walls	4712mm ²	628mm ²		2,254mm ²
Total Area	6126mm ²	12,655mm ²	18,781mm ²	14,280mm ²
Volume of Cylinders	35343mm ³	13,744mm ³	49,087mm ³	49,087mm ³

The table shows how the two systems compare. For the MUSIC system the total surface area is made up of the combustion chamber and the area above the piston. The chamber is a simple cylinder 30mm in diameter and 50mm long. For both engines the main cylinder is 87.5mm diameter and for the conventional engine the length of the cylinder (cylinder head to top of piston) is 8.2mm whilst for the MUSIC system the length is 2.3mm. In order to simplify the calculations the cylinder head in the conventional engine has been converted from a pent roof design to a flat top layout. The MUSIC head is flat top anyway.

Since 72% of the air is in the combustion chamber then, theoretically, up to the point of 72% load combustion only takes place in the chamber. It is only above this point that combustion takes place in the main cylinder as well. Even then the combustion in the main cylinder is still lean up to the point of full load.

Therefore, even though once the main cylinder comes into use the surface area is considerably more than the conventional engine, the heat loss is still minimised as a result of the temperature dilution due to the lean running. The table below shows how the lean burn dilution coupled with the reduction in surface area leads to major reductions in heat loss.

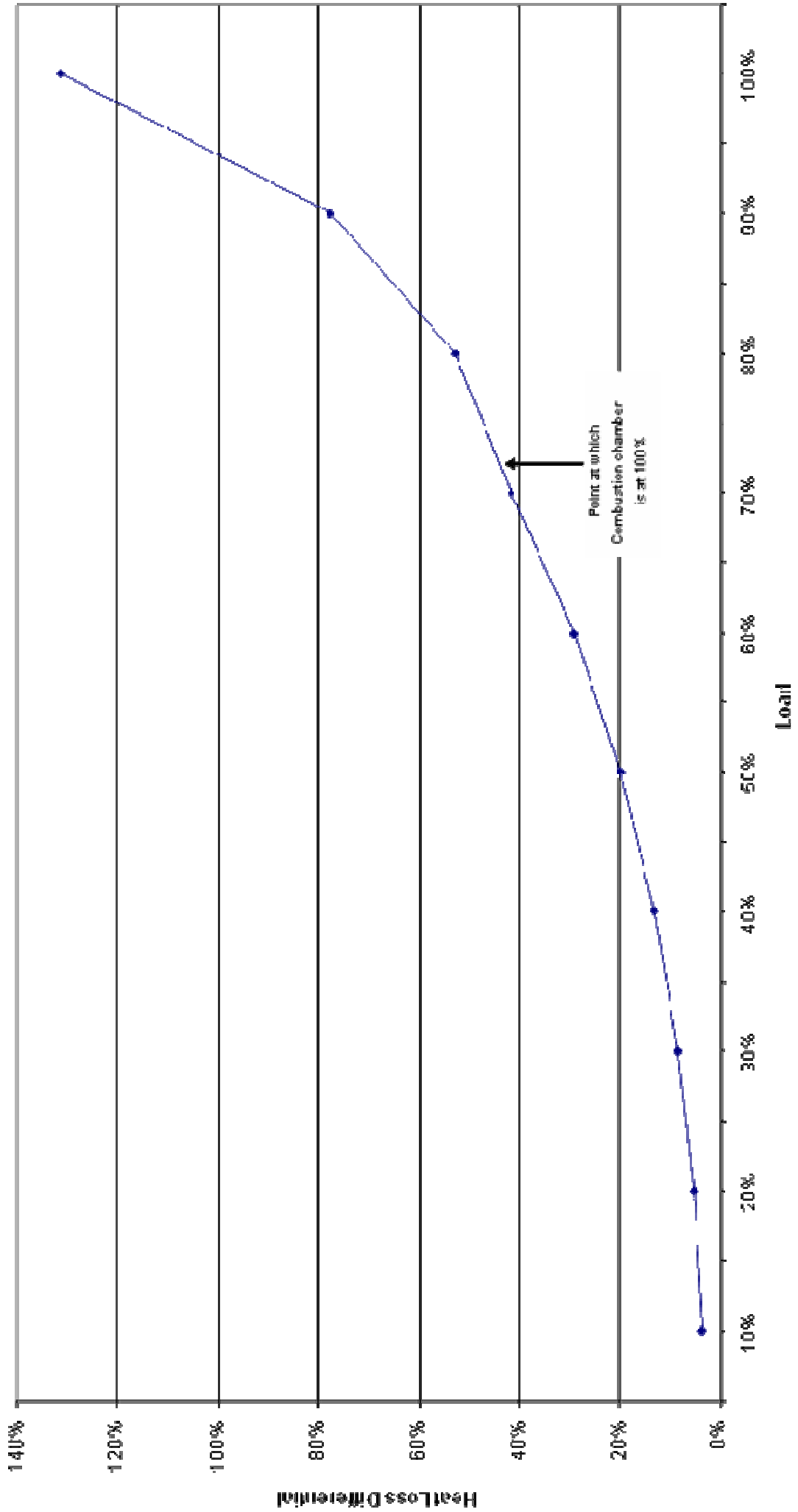
Engine Load	% Chamber	Temp in chamber K	Main Cyl Temp K	Music Heat Loss	Conventional Heat Loss	MUSIC as % of Conv.
10%	14%	962	778	9.5E+15	2.8E+17	3.4%
20%	28%	1145	778	1.5E+16	2.8E+17	5.3%
30%	42%	1329	778	2.3E+16	2.8E+17	8.4%
40%	56%	1513	778	3.6E+16	2.8E+17	13.1%
50%	69%	1696	778	5.5E+16	2.8E+17	19.8%
60%	83%	1880	778	8.1E+16	2.8E+17	29.1%
70%	97%	2063	778	1.2E+17	2.8E+17	41.6%
80%	100%	2100	1214	1.5E+17	2.8E+17	52.8%
90%	100%	2100	1664	2.2E+17	2.8E+17	77.8%
100%	100%	2100	2100	3.6E+17	2.8E+17	131.6%

The left hand column shows the % engine load whilst the next column translates this into the equivalent percentage of load in the combustion chamber. This column shows how, at 72% load, the chamber gets to 100% and the combustion then also takes place in the main cylinder.

The two temperature columns show the temperature in both the chamber and cylinder. These temperatures are based on a burn temperature of 2,100°K. The remaining air is taken as being at 778°K at the end of the compression stroke with a compression ratio of 11.5:1. The right hand column shows the heat rejection from the MUSIC engine expressed as a percentage of a conventional engine. The dramatic thermal advantage of the MUSIC system can be seen where, at the lightest load, MUSIC has only 3.4% of the heat loss of a conventional engine (96.6% improvement). Even at 50% load the improvement is still around 80%. It is only at 95% load that the heat loss from the MUSIC becomes greater than a conventional engine. However in typical usage an engine spends minimal time at loads greater than 95%. This penalty is therefore outweighed many times by the huge benefits in the sub 50% load region where engines spend most of their lives operating lives.

The thermal benefit is illustrated in the following graph.

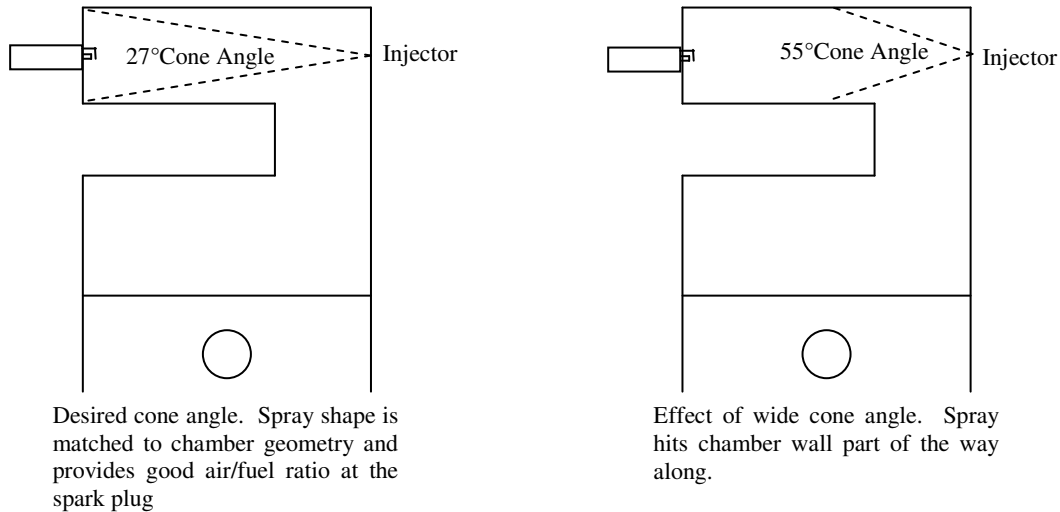
MUSIC Heat Loss expressed as a Percentage of a Conventional



Injector Characteristics

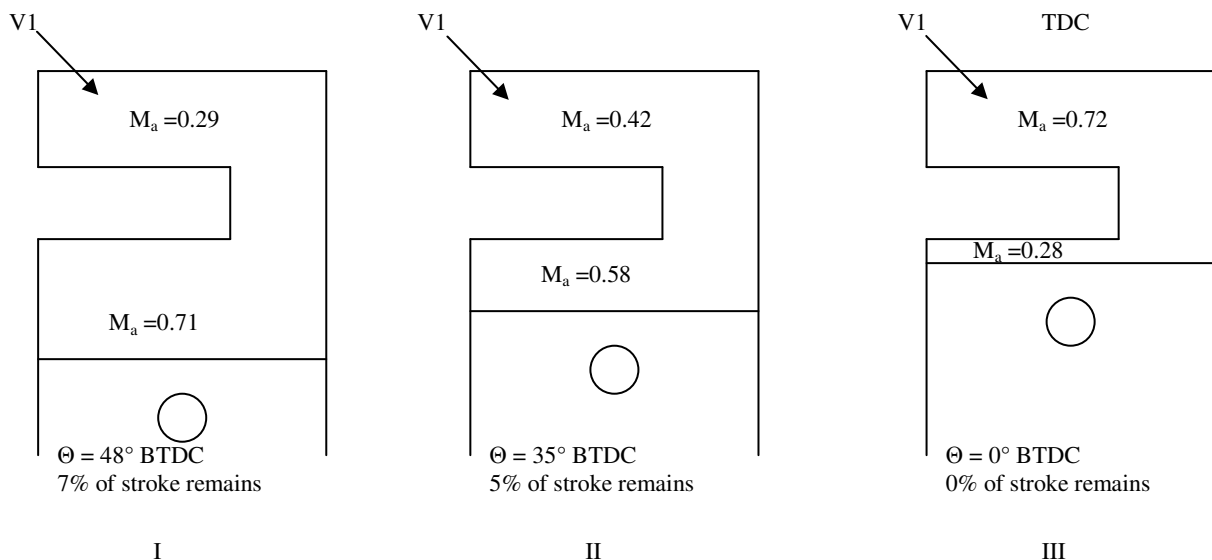
In order to understand the injector requirements it is necessary to keep in mind the geometric properties of the combustion chamber and the varying rate of transfer of air mass into the chamber during the compression stroke. The varying rate of transfer is as a result of the non-linear motion of the piston in a reciprocating engine.

Required Spray Geometry



These diagrams show how the fuel spray cone angle is critical to ensuring that the fuel is delivered to the correct place in relation to the spark plug. Too wide a spray and the fuel impinges on the chamber wall part of the way along which leads to very poor stratification and an incorrect mixture at the spark plug. For the current design a spray angle of 27° places all the fuel in the correct region, however an optimum design would actually be for a hollow cone of fuel as this would actually place the fuel in the correct place for both the spark plug and the air mass which is concentrated around the periphery due to the centrifugal force created by the swirling motion of the air.

Air Mass Transfer into Combustion Chamber

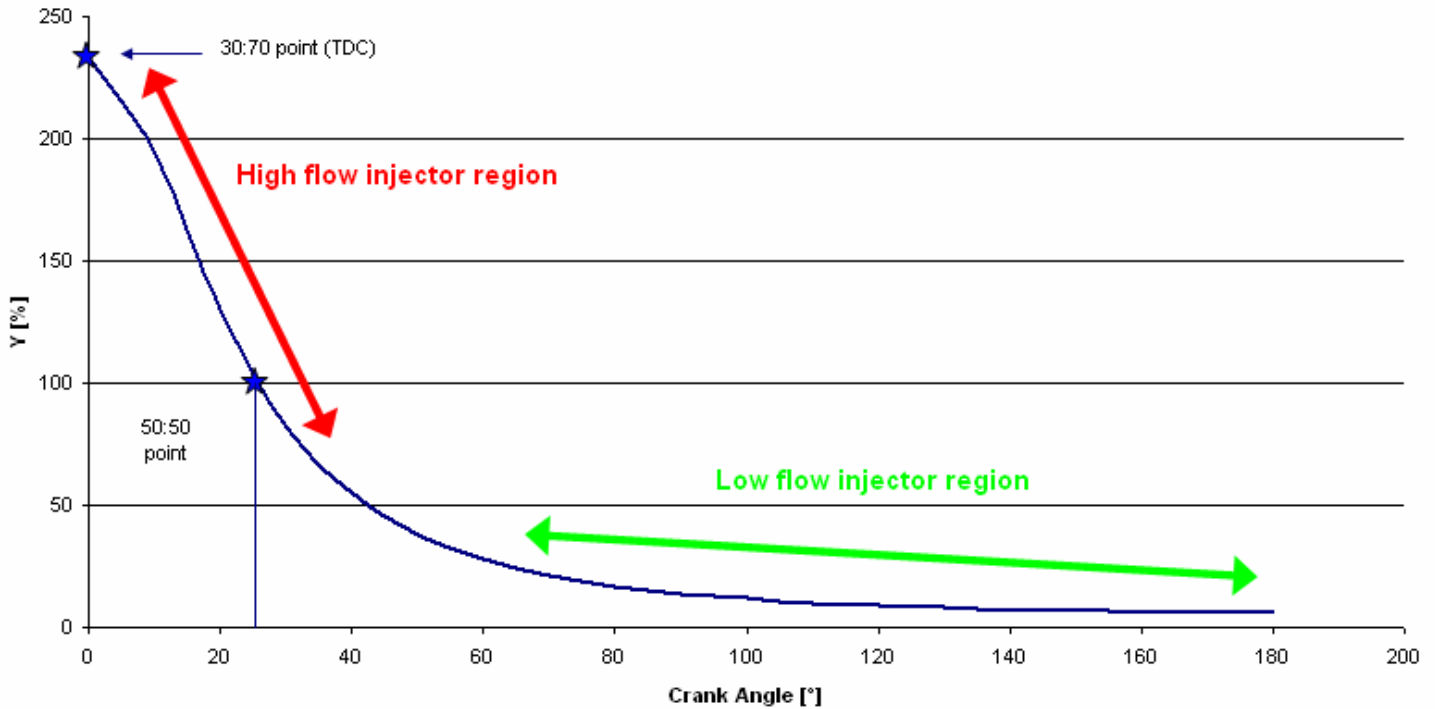


I to III. In the last 48° (7%) of the stroke 43% of the air mass moves into the chamber

II to III In the last 35° (5%) of the stroke 30% of the air mass is transferred into the chamber

The preceding diagrams demonstrate that the rate of air transfer into the chamber is not linear with respect to crank angle. The following graph illustrates this aspect.

Air Mass in Combustion Chamber as an Idealised Percentage of the Air Mass in the Main Cylinder During the Compression Stroke



This varying rate of air transfer has a direct impact on the rate at which we need to inject fuel. In an ideal situation we would have an injector which had a varying rate of fuel delivery designed to precisely match the air transfer rate. Injectors such as these are now coming into production on the latest generation of gdi Spray Guided engines. However, as has been discussed previously such an injector was not available to the project. Therefore it is necessary to vary the flow by pulsing the injector (ie operating the injector for different durations several times during each cycle).

Unfortunately the project was not able to attract the support of any injection system manufacturer either in the design of an injector to suit our requirements or in the supply of an ECU to enable us to pulse the injectors. Therefore, in order to overcome this lack of support the project had to find a way to utilise existing off-the-shelf components.

The solution arrived at was to use two injectors, one with a high flow rate and one with a low flow rate. These injectors would be operated by independent controllers timed to fire rapidly one after the other and thus to imitate the action of a pulsed system. However, due to the physical size of an injector it was necessary to locate the second high flow injector in a different position (it not being possible to locate them together). The chosen position for the high flow injector was at 90° to the low flow unit with the injector firing directly into the air stream coming up through the transfer port as shown to the right.

