

The Effect of Piston Cooling Jets on Diesel Engine Piston Temperatures, Emissions and Fuel Consumption

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ABSTRACT

A Ford 2.4 litre 115PS light-duty diesel engine was modified to allow solenoid control of the oil feed to the piston cooling jets, enabling these to be switched on or off on demand. The influence of the jets on piston temperatures, engine thermal state, gaseous emissions and fuel economy has been investigated. With the jets switched off, piston temperatures were measured to be between 23 and 88°C higher. Across a range of speed-load points, switching off the jets increased engine-out emissions of NO_x typically by 3%, and reduced emissions of CO by 5-10%. Changes in HC were of the same order and were reductions at most conditions. Fuel consumption increased at low speed, high load conditions and decreased at high speed, low load conditions. Applying the results to the NEDC drive cycle suggests active on/off control of the jets could reduce engine-out emissions of CO by 6%, at the expense of a 1% increase in NO_x, compared to the case when the jets are on continuously. The corresponding change in fuel consumption would be insignificant.

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INTRODUCTION

The lubricating oil of engines is commonly exploited as a secondary cooling medium to limit piston temperatures and piston internal temperature gradients in turbocharged diesel and spark ignition engines. Typically, jets of oil are directed onto the underside of the piston or into an internal gallery in the piston or a combination of these. Agarwal and Varghese [1] describe three arrangements of gallery and oil jets, and present the results of numerical investigations showing the influence of enhanced cooling on the temperature distribution in the piston of a medium duty, direct injection diesel. In the standard arrangement the oil jets are on continuously, though there is no thermal protection requirement for this over a large part of the engine operating map and the benefits to engine performance and emissions more generally, are unclear. The aim of the study reported here was to investigate some of these uncertainties and examine the merits of being able to switch the jets on or off.

The use of engine oil to cool pistons has a long history. Early work by Bush and London [2] and French [3] on promoting heat transfer was directed at limiting piston temperatures in large, low-speed diesels, principally for marine or power generation applications. For these low speed

engines, they demonstrated the benefits of directing oil to partly fill an internal gallery in the piston. Heat transfer in the gallery was enhanced by the so-called cocktail shaker effect produced by the unconstrained movement of oil. In relatively recent work [4], numerical simulations indicated enhanced cooling of the piston could change piston temperature by as much as 300 deg C. In the 1990's, greater attention was given to piston cooling for smaller, turbocharged diesels operating at higher engine speeds. Piston temperature was one of the factors limiting the power densities required for these by the automotive industry. Leites and De Camargo [5] showed that at the higher operating speeds, piston temperature decreased with increasing flow rate of oil injected into piston gallery up to a critical rate when the jet velocity equalled the maximum piston speed; beyond this, further increases in flow rate had a much reduced effect. Temperature fell by around 60 deg C over a threefold increase in oil flow rate up to the critical rate. An alternative to directing oil jets into an internal gallery of the piston is to aim the jets at the piston underside surface. This supplements oil thrown naturally onto the piston by the rotation of the crankshaft. According to the numerical simulations presented by Pimenta and Filho [6], changing the point of jet impingement could produce piston temperature

changes by as much as 50 deg C, all other parameters being constant. An optimum radial impingement position was found to exist at around 1/3 of the piston radius. A different approach to piston cooling, using heat pipes, was investigated by Cao and Wang [7], and Wang, Cao and Souto [8]. In this approach, heat pipes containing a fluid heat transfer medium are incorporated in the piston and extend from behind the ring pack down to the piston skirt. Their analysis suggested designs of heat pipe could be produced to enhance heat transfer at shaking frequencies above $\sim 7\text{Hz}$, making them suited to piston heat transfer applications. They predicted piston underside heat transfer could be increased by around an order of magnitude.

Most of the literature on piston cooling is concerned with the effect on piston temperatures. The influence on factors such as oil temperature, coolant heat rejection and exhaust gas emissions are covered less well. Piston temperature is known to have an effect on the exhaust emissions of a combustion engine. In an early study of the effect on diesel emissions, Slezak and Vossmeier [9] recorded a reduction in no-load HC emissions of 25 to 33% when cylinder wall temperature was increased by 60 deg C. In work on a direct injection gasoline engine, Frank and Heywood [10] considered whether effects on HC emissions derive directly from changes in piston temperature, or indirectly from the piston's thermal interactions with the inducted air charge. They concluded that the main effect on HC emissions arose indirectly through the influence of piston temperature on charge heating. For homogeneous charge engines, the top land crevice is an important source of unburned HC and piston temperature effects the clearance which was shown to be important dimension by Christianson et al [11] and Seabrook et al [12], pointing to a potential disadvantage of overcooling using oil jets.

A Ford 4 cylinder, 2.4 litre 115PS light-duty diesel engine was modified to support the studies reported here. The engine is a direct-injection, turbocharged unit with pistons which have an internal gallery in the piston crown fed by an oil cooling jet directed at an entry hole on the underside of the piston. Oil is fed from the main gallery to nozzles rigidly mounted on the crankcase at the bottom of each cylinder liner. As the piston approaches and leaves its lowest position in a crank revolution, the oil nozzle mates with a drilling in the piston skirt and a fresh charge of cooling oil is fed in. Oil drains from the gallery by means of a drilling in the opposite skirt. The nozzles have a simple ball valve, designed to open at approximately 150kPa gauge pressure. This shuts off the nozzle flow at hot idling conditions, but the nozzles are open at most other conditions. The engine was modified in two areas, the first to supply the oil nozzles through separate pipe-work with a solenoid valve allowing the piston cooling jets to be switched on and off at any running condition, and the second to fit instrumented pistons and a wireless pick up system allowing piston temperatures to be recorded. The pistons and the wireless system were supplied by Federal Mogul. A range of instrumentation has been used in previous

investigations of piston temperature, including thermal plugs, thermocouples and thermistors [13]. For the current work, two pistons were instrumented with 3 thermistors each, covering 6 locations in total. The locations are shown in [Figure 1](#). Thermistor numbers 2 and 3 failed during commissioning; the other four worked throughout the test programme. These recorded temperatures in the piston behind the top groove (1), just beneath the bowl (4), at the bowl edge (5) and near the underside of the crown (6). Each thermistor was linked to its own inductive pickup circuit, wherein a female wire coil (moving with the piston) mated with a male coil (stationary at the bottom of the liner), every time the piston passed BDC. In this way, the piston temperature signal was updated every crankshaft revolution. The measurable temperature range was limited at the low end to 100°C by the minimum temperature requirement for accurate operation of the thermistors, and at the high end to 350°C by the need to avoid overheating the pistons with the jets off.

PISTON TEMPERATURE RESULTS

Piston steady-state temperature data are given in [Tables A1](#), [A2](#) and [A3](#). These set out results for fully-warm running conditions covering speeds from 800 to 4000 rev/min and brake loads from 0 to 1400 kPa BMEP. Within these ranges, temperatures were not recorded at some combinations of load and speed either because the measurement limits of the thermistors or the upper limits on engine brake load were reached. Areas of light load and low to moderate engine speed were excluded because piston temperature did not reach 100°C. At high loads, and all speeds except 2000 rev/min, the limiting factor was brake load. At 2000 rev/min, with the cooling jets off, the temperature at the bowl edge reached 350°C before brake load reached 1400 kPa and this setting was excluded from the test matrix.

For jets-on operation, bowl edge temperatures were the highest, followed by under-crown temperatures, then bottom-of-bowl and top groove. Temperatures at these last two locations were generally similar. With the cooling jets switched off, the bowl edge and under-crown temperatures remain the highest, but temperature beneath the bowl rises to near the under-crown temperature. The top groove temperature remains the lowest. The location most strongly affected by the presence of cooling jets is the combustion bowl bottom which, as can be seen in [Figure 1](#), is closest to the oil gallery. In this location, switching on cooling jets reduced metal temperature by between 42°C at light load and 88°C at high load. Similar trends but smaller changes of between 25°C and 65°C were recorded for the other locations. The complete map of temperature reductions is given in [Table A3](#).

The response of piston temperatures to switching the oil jets either off or on is illustrated in [Figure 2](#) and [Figure 3](#), respectively. The switch occurs at time $t=0$ in both cases. When the jets are switched off, piston temperatures at the top groove, edge of the bowl and undercrown location rise at a

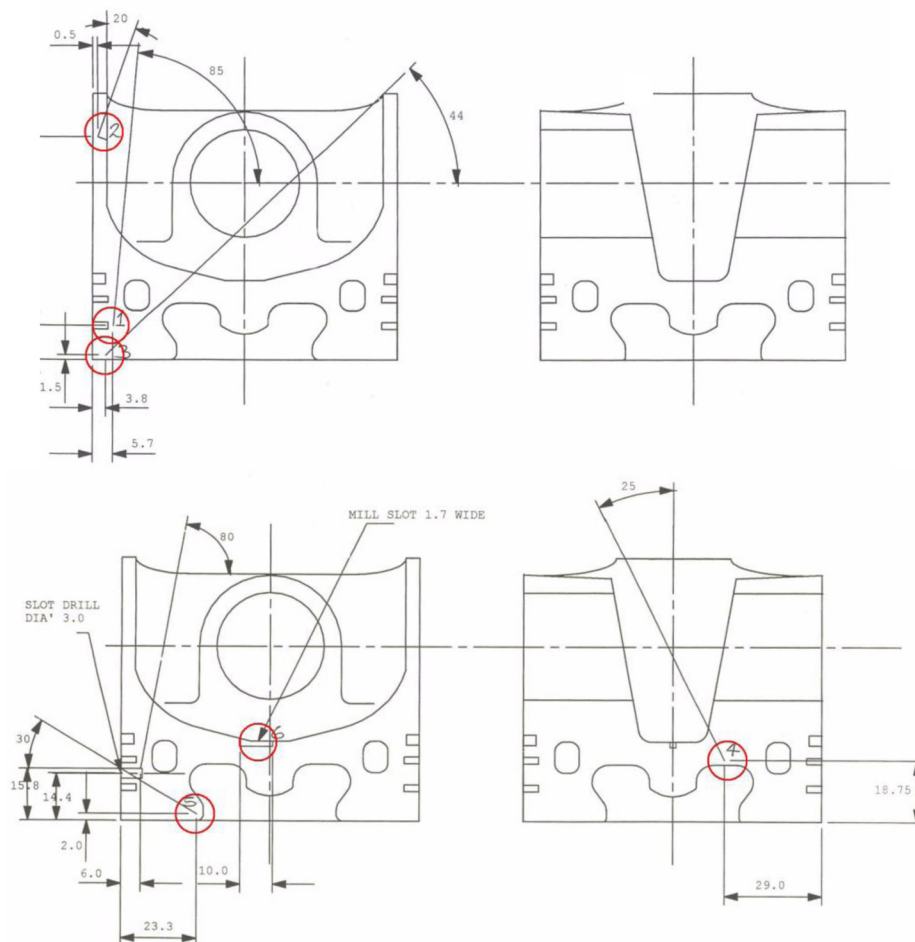


Figure 1. Locations of Piston Thermistors. 1: Top Ring Groove. 2: Lower Skirt. 3: Top Land. 4: Bowl Bottom. 5: Bowl Edge. 6: Under Crown.

similar rate and maintain temperature differences; the temperature beneath the bowl is most affected by switching off the jets and shows a greater increase. The pattern of temperature changes is reversed when the jets are switched on, lowering temperatures. The largest change is again in the temperature beneath the bowl. The response time depends on whether the jets are being switched on or switched off. When the jets are switched on, the rate of change of temperature is around twice that after the jets are switched off. The rates of change dT/dt of the instantaneous, average values are compared in Figure 4. The time taken for dT/dt to reach less than $0.1^{\circ}\text{Cs}^{-1}$ is approximately 50 seconds when the jets are switched on and 90 seconds when the jets are switched off. The initial rate of piston temperature rise when the jets are switched off is significantly less, only 1/2, the rate of fall when the jets are switched on. The net energy lost and gained by the piston is the same, so the difference must reflect the initial thermal condition of the piston and relative heat transfer magnitudes of jet cooling and “splash” cooling (which is the main piston underside cooling mechanism present when the jets are off).

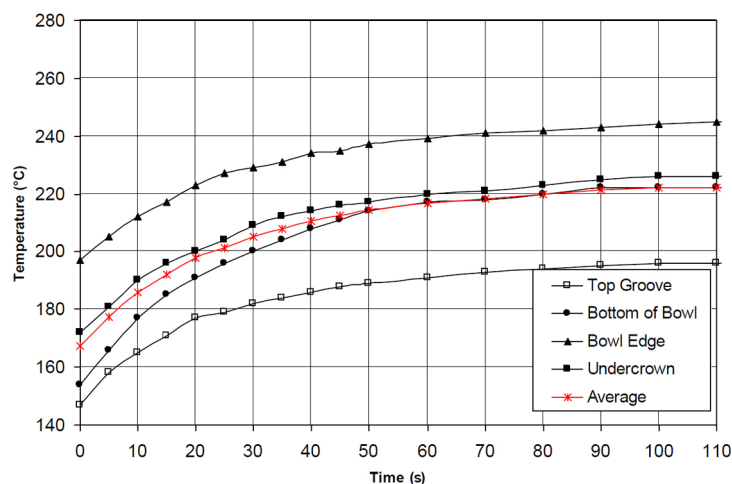


Figure 2. Transient response of the measured piston temperatures to the oil jets being switched off. 2000rpm, 8Bar BMEP.

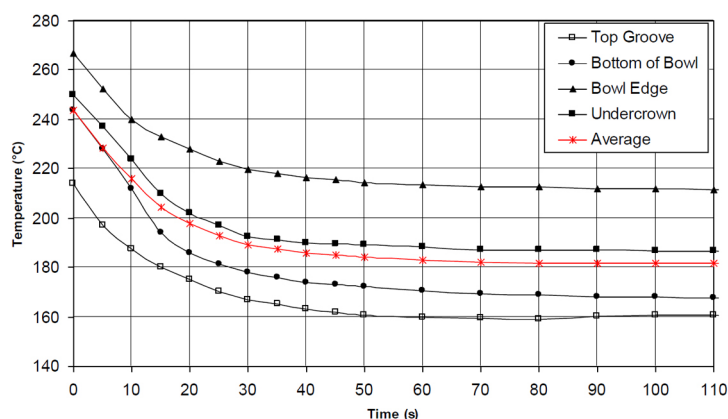


Figure 3. Transient response of the measured piston temperatures to the jets being switched on. 2000rpm, 8Bar BMEP.

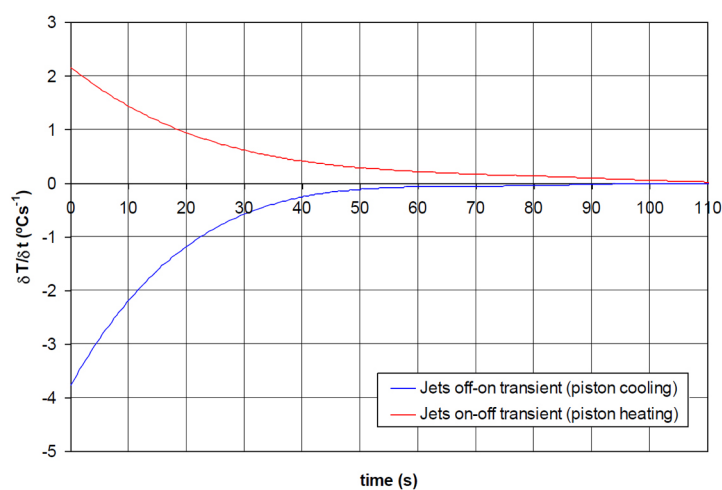


Figure 4. Gradient, dT/dt of the average piston temperature transient response to Cooling Jet switching.

INFLUENCE ON ENGINE HEAT BALANCE AND PATH TO COOLANT

The main heat exchange pathways for the piston are illustrated in Figure 5, and when the oil jets are switched on or off, the redistribution of heat flow has a more global influence on engine thermal state. The results presented in Figures 6,7,8 show temperature responses to switching the oil jets off when the engine was operating fully-warm at conditions of 2000rpm, 8Bar BMEP.

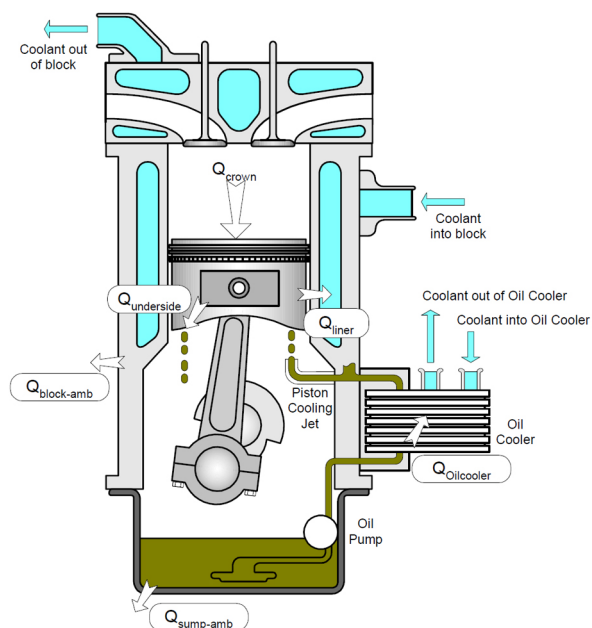


Figure 5. Schematic view of primary heat fluxes in the engine when piston cooling jets are employed.

As shown in Figure 6, the temperature of oil in the sump and flowing through the main gallery fell by around 5°C over 300-400s when the jets were switched off and direct heat transfer from the piston to the oil in the jets eliminated. Liner metal temperatures were measured at three locations on the anti-thrust side of cylinder number 4, corresponding to the BDC and TDC ring-reversal positions, and the mid-stroke. All liner thermocouples were placed at depths of 1mm under the cylinder wall. Liner temperatures moved in the opposite direction to those of sump and main gallery oil (Figure 7), rising by between 1 to 3°C and stabilising slightly more quickly. The larger rises occurred towards the bottom of the liner.

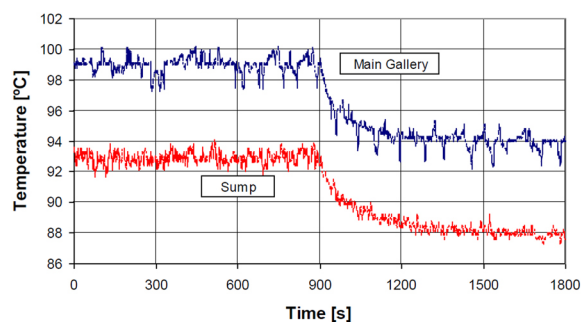


Figure 6. Main Gallery and Oil Sump temperature change when cooling jets are turned off at $t = 900s$.