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Charge Cooling, the Inlet and Exhaust Systems

9.1 Charge Cooling

The principal reason for turbocharging is to increase the power output of an engine without increasing its size. This is achieved by raising the inlet manifold pressure, hence increasing the mass of fresh air drawn into the cylinders during the intake stroke and allowing more fuel to be burnt. However, it is impossible to compress air without raising its temperature unless the compressor is cooled. Since the objective is to raise the density of the air, this temperature rise partly offsets the benefit of increasing the pressure, since

\[ \rho = \frac{P}{RT} \] (9.1)

The objective must therefore be to obtain a pressure rise with a minimum temperature rise. This implies isentropic compression (figure 9.1) in which case the temperature rise will be given by the equation

\[ \Delta T_s = (T_2 - T_1)_s = T_1 \left[ \frac{(P_2/P_1)^{(\gamma-1)/\gamma}} - 1 \right] \] (9.2)

Unfortunately due to inefficiencies in practical compressors, the actual tem-

Figure 9.1 Charge air cooling, with a pressure loss

N. Watson et al., Turbocharging the Internal Combustion Engine
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perature rise will be greater than that given by equation 9.2. In terms of the isentropic efficiency of the compressor (\(\eta_c\)) it will be given by

\[
\Delta T = T_2 - T_1 = (T_2 - T_1) / \eta_c = T_1 \left[ \frac{(P_2/P_1)^{(\gamma-1)/\gamma} - 1}{\eta_c} \right] \tag{9.3}
\]

The more efficient the compressor, the closer the temperature rise approaches the isentropic temperature rise (figure 9.1).

Denoting states 1 and 2 as the inlet and outlet to the compressor, and using equations 9.1 and 9.3

\[
\rho_2 = \frac{P_2}{RT_1} \left[ 1 + \left( \frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} \right] / \eta_c \tag{9.4}
\]

or

\[
\rho_2 / \rho_1 = \left( \frac{P_2}{P_1} \right) \left[ 1 + \left( \frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} \right] / \eta_c \tag{9.5}
\]

Equation 9.5 is plotted in figure 9.2 for a range of pressure ratios and compressor efficiencies. Several points emerge. Firstly, the benefit obtained by raising inlet manifold pressure is reduced substantially due to the temperature rise in the compressor, which itself is dependent on compressor efficiency. Secondly, the advantage of high compressor efficiency in helping to hold the boost temperature down is relatively small, but worthwhile. Thirdly, in absolute terms, the benefit that can be obtained by cooling the compressed air back to near ambient conditions is substantial, and increases with pressure ratio. Clearly it is attractive to try to cool the air between compressor delivery and the intake to the cylinders.

A further advantage of charge cooling is that the lower inlet temperature at the cylinders will result in lower temperatures throughout the working process of the engine (for a specified BMEP) and hence reduced thermal loading. Figure 9.3 illustrates the compressor outlet temperature variation with pressure ratio and compressor efficiency for a typical inlet condition. In terms of delivery temperature, the benefit of correctly matching the turbocharger such that the

![Figure 9.2 Effect of compressor efficiency on air density in the inlet manifold](image-url)