Temperature of diesel fuel spray at injector nozzle hole exit

Perkins Technology

1 Background

Fuel is injected into the cylinder of a diesel engine through a high-pressure injection system. For the particular system considered by Perkins Technology, fuel at a temperature of about 300 K arrives in the injector at approximately 1400 bar and is then injected into the cylinder in 1.5 ms by raising a needle and uncovering the nozzle holes. The relevant portion of the injection system is shown in figure 2. The cycle period between injections is 40 ms. Each injection contains 85 mm^3 of fluid. This corresponds almost exactly to the amount of fuel stored in the annulus around the needle below the spherical reservoir. The physical quantity of interest is the temperature of the fuel when it is injected into the cylinder. Temperature measurements in the fuel storage volume are hard to make. A thermocouple placed in the wall of the injector tip, however, has measured a temperature of 550 K.

Physical constants appropriate for fuel were supplied by Perkins Technology. Representative values for these and for the physical constants for steel are given in table 1.

2 Various aspects of the heat transfer

(a) The Reynolds number ud/ν (based on annulus thickness d) of the flow during the injection cycle is around 10^4, corresponding to an average speed of $u = 30$ ms^{-1}. During injection the wall boundary layer thickness $\delta = \sqrt{\nu t} \leq 4 \times 10^{-2}$ mm is much smaller than d. Hence the injection flow down the straight annulus is laminar plug flow. In addition, vorticity is flushed out and fluid is quiescent between injections.

(b) The complicated geometry in the nozzle itself will lead to turbulent flow in that region, and hence to efficient heat transfer there during injection. This might be important, since the temperature in the wall in that region is high (550 K).

	k	ρ	c_p	κ	$\alpha = k/\sqrt{\kappa}$	ν
steel	100	8,000	500	25×10^{-6}	20,000	—
fuel	0.15	800	2,000	0.1×10^{-6}	500	10^{-6}

Table 1: Physical properties in SI units. k: thermal conductivity, ρ: density, c_p: specific heat capacity, κ: thermal diffusivity, ν: kinematic viscosity.

(c) Adiabatic cooling might be expected to lead to a decrease in temperature of $p^2/2K$ where K is the bulk modulus of the fuel. The high input pressure of 1400 bar leads to a possible cooling of 6 K, which is non-negligible.

(d) If all the kinetic energy $\frac{1}{2}u^2$ were dissipated as heat $\rho c_p \Delta T$, then $\Delta T \approx 0.2$ K, which is small. Moreover, the dissipation is actually a small fraction of the kinetic energy.

3 Conduction in the annular region

The heat transfer into the fuel in the annulus between the needle and the wall of the injector during the quiescent phase is clearly one of the major contributions. After each injection, the new fluid in the annulus is at a temperature $T_0 \approx 300$ K, while the outer face of the injector is at an unknown temperature T_B. This is an averaged temperature; in reality, there will be a temperature gradient along the outside wall of the injector. The needle is surrounded by fuel at all times and remains at T_0. The quantity $\sqrt{\kappa t_c}$, where t_c is the duration of the quiescent cycle, gives the 'penetration depth' of the change of temperature across the inner wall. This is a small distance (1 mm for steel, and 1/15 mm for fuel), but the heat flux into the fuel is nevertheless significant. During the injection phase, the profile returns to its original form.

The steady profile in the steel is the logarithmic profile

$$T = T_A + (T_B + T_A)\frac{\ln(r/r_0)}{\ln(R/r_0)} \tag{1}$$

where r_0 and R are the inner and outer radii of the injector wall. This temperature profile is the solid line in figure 1. During the quiescent phase, the temperature profile within the steel and fuel will evolve to the dashed profile. The temperature in the steel will then be given by (cf. [1])

$$T = T_0 + \frac{\alpha_s}{\alpha_f + \alpha_s}\left(1 + \frac{\alpha_f}{\alpha_s}\operatorname{erf}\frac{x}{2\sqrt{\kappa_f t}}\right)(T_A - T_0), \tag{2}$$

where t is time after injection, and x the distance from the wall. The geometry is taken to be planar except for the logarithmic dependence of the basic profile in (1). Hence the heat flux at the wall is

$$q_f = \frac{\alpha_f \alpha_s}{\alpha_f + \alpha_s}\frac{T_A - T_0}{\sqrt{\pi t}}; \tag{3}$$

the first fraction may be replaced by α_f since the value of α is much greater for steel than for fuel (by a factor of 40). The heat flux into the steel is

$$q_s = \frac{k_s}{r_0 \ln(R/r_0)}. \tag{4}$$

Equating the time-integrals of these values over the duration t_c of the quiescent cycle leads to

$$\frac{\alpha_f}{2}\sqrt{\frac{t_c}{\pi}}(T_A - T_B) = \frac{k_s t_c}{r_0 \ln(R/r_0)}. \tag{5}$$

The second quantity is much bigger than the first, and so $T_A \approx T_B$.

The heat capacity of the fuel inside the annulus is given by $(r_o - r_i)\rho c_p = (r_o - r_i)\alpha_f/\sqrt{\kappa_f}$. Hence the rise in temperature of the fuel is given by

$$\Delta T_f = \sqrt{\frac{t_c}{\pi}} \frac{\sqrt{\kappa_f}}{2(r_o - r_i)} \Delta T_s \approx \frac{1}{17} \Delta T_s, \tag{6}$$

where ΔT_s is the difference in temperature between the initial fuel temperature T_0 and the inner wall temperature T_B. In other words, a difference in temperature of 1 K at the inner wall leads to a rise of 1/17 K in the fuel at the end of the cycle.

4 Convection in the nozzle region

At the very end of the injector near the nozzle, the flow during the injection period will be extremely turbulent, and will convect heat away efficiently out of the walls of the device into the fluid. From the Perkins note sheets, a generous estimate of the volume of fluid in this section of the nozzle is 2 mm^3. The thermocouple measurement of 550 K in the wall around this region indicates that there is a large temperature difference there, of the order of 250 K. The consequent average rise in temperature in the whole fluid (i.e. the 85 mm^3 injected) is

$$\Delta T \approx 250 \times \frac{2}{85} \times 2.5 \approx 15 \text{ K}. \tag{7}$$

5 Conclusion

The various contributions to the change in temperature of the fluid can be summarised as

(a) −5 K from the adiabatic cooling

(b) 15 K from the convection near the nozzle

(c) $\Delta T_s/17$ from the conduction in the annulus. This depends on the average temperature of the wall of the annulus, which is unknown, but certainly between 300 and 550 K, corresponding to ΔT_s = 0–250 K. Hence the smallest and largest rises in temperature are 0 and 15 K respectively.

The maximal rise in temperature of the fluid is hence 25 K. A more likely estimate might be 10 K.

Some useful data, in the absence of actual heat measurements inside the fuel reservoir around the needle, would be the temperature of the wall T_B. Knowledge of its spatial variation would also be of interest, since it has just been been treated as an average in this report.

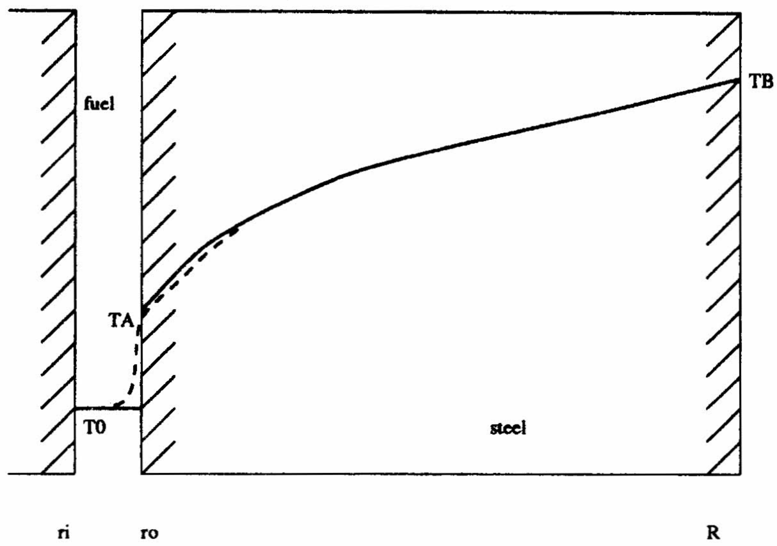

Figure 1: The annular region between the needle and the wall of the injector. The geometry is modelled as plane. The solid line is the initial temperature profile of the fuel and steel at the beginning of the quiescent part of the cycle. The dashed line is the profile at the end of the quiescent period. *Not to scale.*

References

[1] H. S. Carslaw and J. C. Jaeger, The conduction of heat in solids, Oxford University Press, 1959.

Participants

John Byatt-Smith, Richard Day, Oliver Harlen, John Lister, Stefan Llewellyn Smith, Colin Please.
With the help of Richard Stone, Sam Howison and Andrew Fowler.