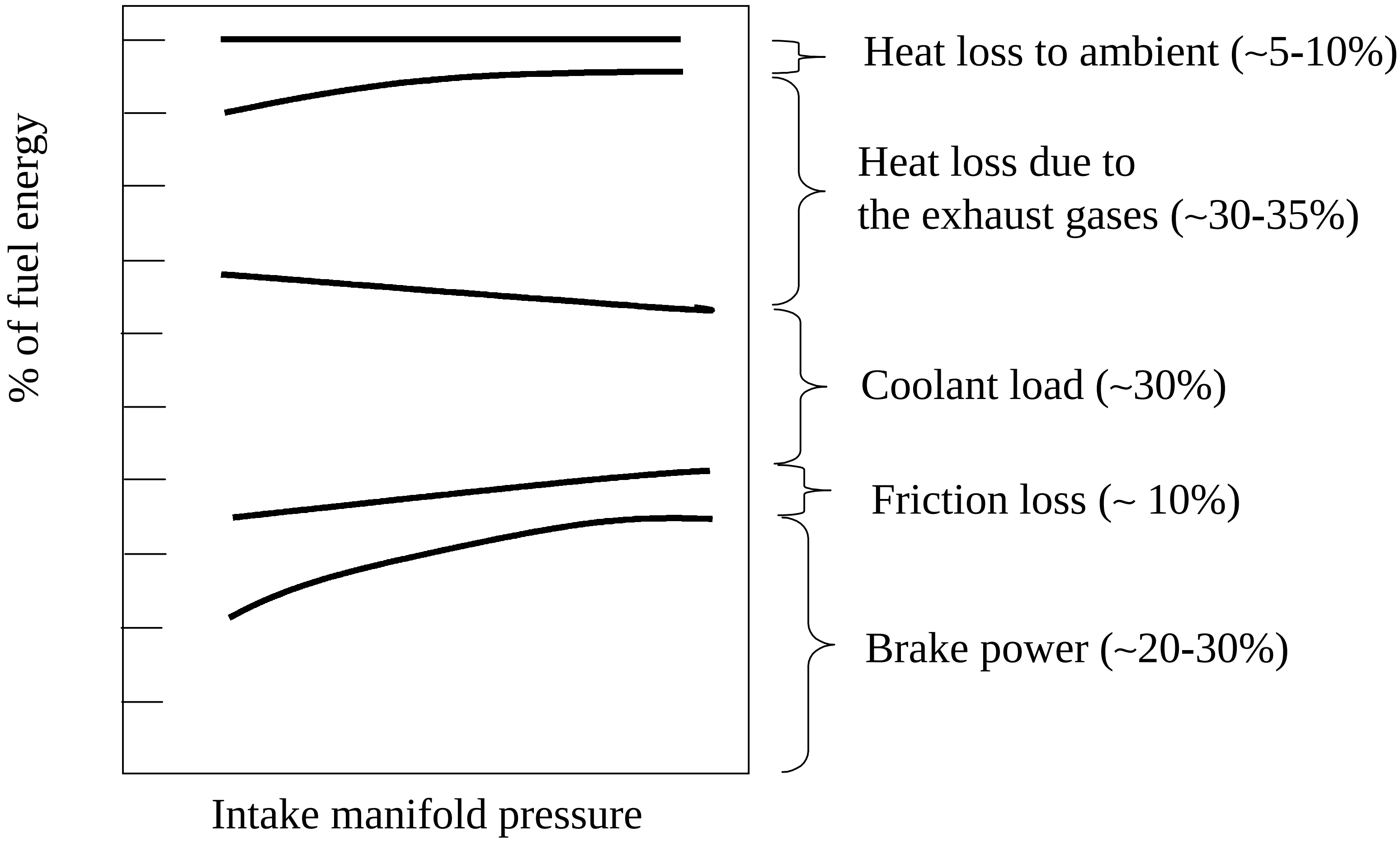
Engine Heat Transfer

- Engine heat transfer is an important design consideration for many practical reasons.
  - Emission control: catalytic converter performance (>500 K)
  - Charge heating: decrease volumetric efficiency
  - Material temperature limitations: thermal barrier, thermal fatigue & stress
  - Engine performance: heat loss leads to lower operating temperature → lower efficiency
  - Lubrication limits: lubricant lose its viscosity, ability to maintain a thin film between surfaces, at high temperature

- All modes of heat transfer are important
  - Conduction: $q = -kA\nabla T$
  - Convection: $q = hA(T_S - T_\infty)$
  - Radiation: $q = \varepsilon\sigma A(T_S^4 - T_{surr}^4)$

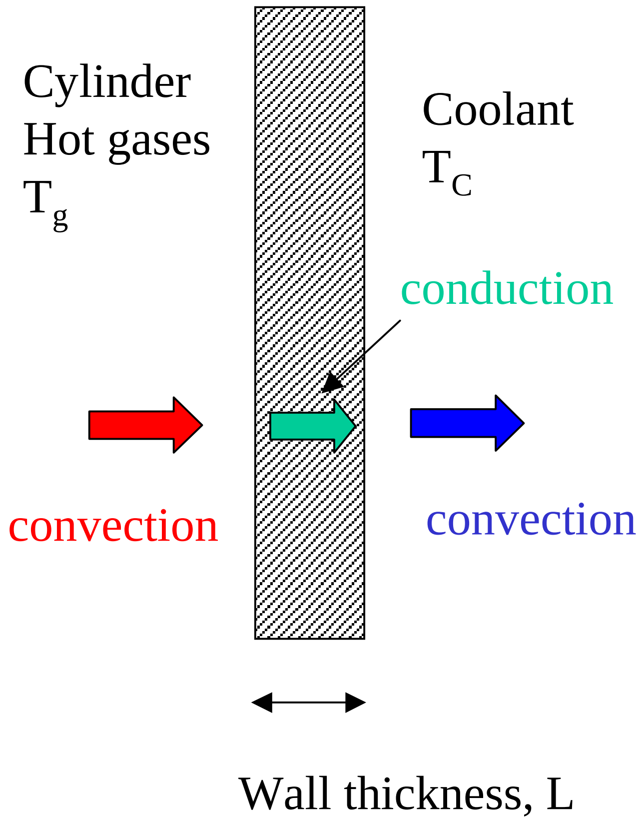
Overall Energy Balance

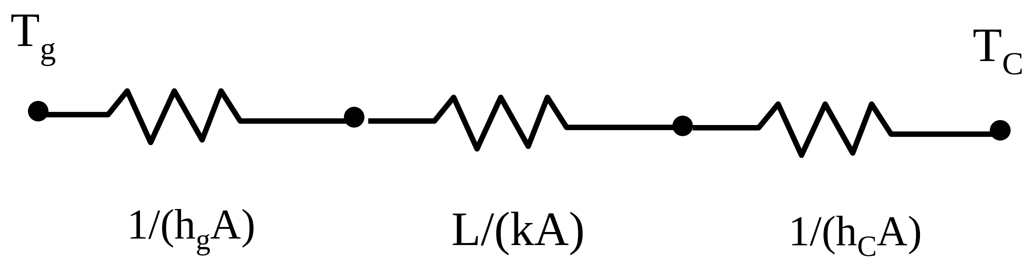


$$\dot{m}_f h_f + \dot{m}_a h_a = P_b + q_{coolant} + q_{ambient} + q_{friction} + (\dot{m}_f + \dot{m}_a)\dot{h}_e$$

(*T*otal available energy)=(Brake power)+(Other losses)+(exhausted energy)

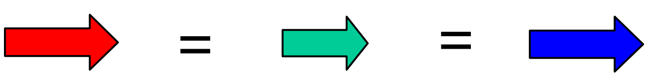
1-D Heat Transfer Model





$$q = \frac{T_g - T_C}{\sum R_{th}} = \frac{T_g - T_C}{\frac{1}{h_g A} + \frac{L}{kA} + \frac{1}{h_C A}}$$

Is the steady state assumption valid ?



For 1-D, steady state heat transfer

Unsteady Heat Penetration

Now, consider the unsteady nature of the problem since the cylinder wall experiences a periodic heat flux from the inside cylinder wall.

The unsteady conduction equation can be written as:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_P} \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) = \alpha \frac{\partial^2 T}{\partial x^2}$$, by assuming k=constant and $\alpha = \frac{k}{\rho c_p}$

The following boundary and initial conditions have to be satisfied:

(1) $T=T_L$ at x=L (Note: this is an assumption to make the problem easier to solve in order to understand the physics of the unsteadiness. In reality, the temperature of the coolant is a constant but the wall is not necessarily a constant. However, the difference is negligible for our case.)

(2) $-k\frac{\partial T}{\partial x} = q_O'' + q_1'' \sin(\omega t)$ at x=0 (Periodic heat flux from the inside of the cylinder.)

(3) $T=T_i(x)$ at t=0 (The initial condition)

Unsteady Heat Penetration

An approximate solution can be derived if the following two conditions are satisfied: $\omega \mathrm{t} \gg 1$ and $\dfrac{\omega \mathrm{L}^2}{2\alpha} \gg 1$. The unsteady temperature field is given as

$$T(x,t) = T_L + \frac{q_O''}{k}(L-x) + \frac{q_1''}{\left(\frac{\alpha}{\omega}\right)^{1/2}} \exp\left[-\left(\frac{\omega}{2\alpha}\right)^{1/2} x\right] \sin\left[\omega t - \left(\frac{\omega}{2\alpha}\right)^{1/2} x - \frac{\pi}{4}\right]$$

$\Rightarrow$ The surface temperature $T(x=0,t) = T_L + \dfrac{q_O'' L}{k} + \dfrac{q_1''}{\left(\frac{\alpha}{\omega}\right)^{1/2}} \sin\left[\omega t - \dfrac{\pi}{4}\right]$

It oscillates with the same frequency as the heat flux with a phase shift of $\dfrac{\pi}{4}$

$\Rightarrow$ The osciallation vanishes approaching x=L since the oscillatory term decays as $\exp\left[\left(-\dfrac{\omega}{2\alpha}\right)^{1/2} L\right]$ and we know $\dfrac{\omega \mathrm{L}^2}{2\alpha} \gg 1$.

Unsteady Penetration Depth

We can define a penetration depth (δ) as the distance where the amplitude of the oscillation decreases to 10% of the value at the surface.

Therefore, the oscillation term is essentially not important further into the wall.

$$0.1 = \exp\left[-\left(\frac{\omega}{2\alpha}\right)^{1/2}\delta\right], \ \delta = -\ln(0.1)\left(\frac{2\alpha}{\omega}\right)^{1/2} = 2.3\left(\frac{2\alpha}{\omega}\right)^{1/2}$$

In general, this is a small value (in the order of mm).

Therefore, only a thin layer close to the inside cylinder wall will actually experience the oscillatory heat flux.

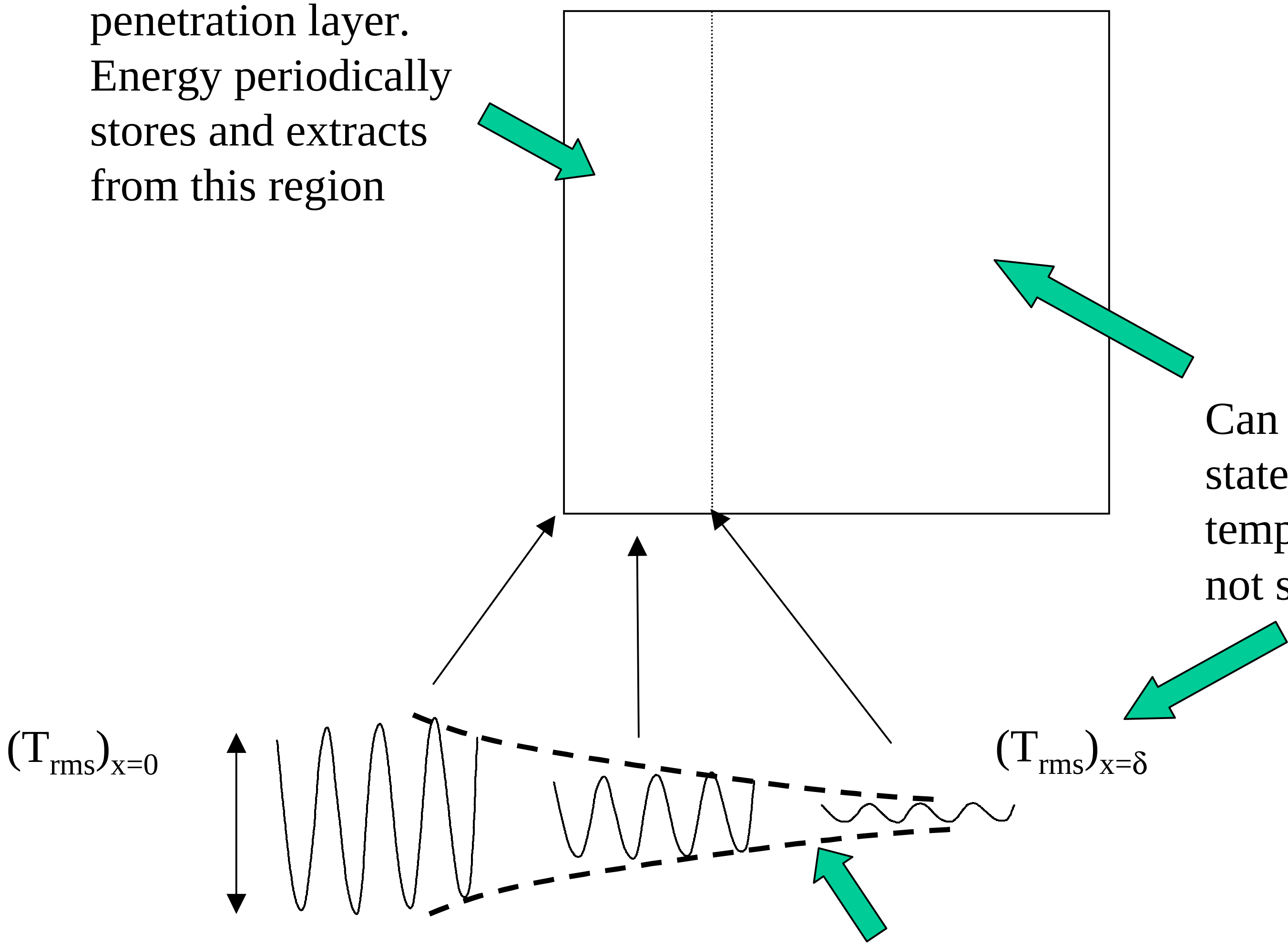
Two simplifications can be introduced:

(1) Beyond x>δ, we can assume steady conduction heat transfer.

(2) The unsteady oscillation can be modelled by using a capacitor to represent the unsteady response inside the penetration layer (see the following two pages).

Penetration Depth

Unsteady response is Important inside the penetration layer. Energy periodically stores and extracts from this region



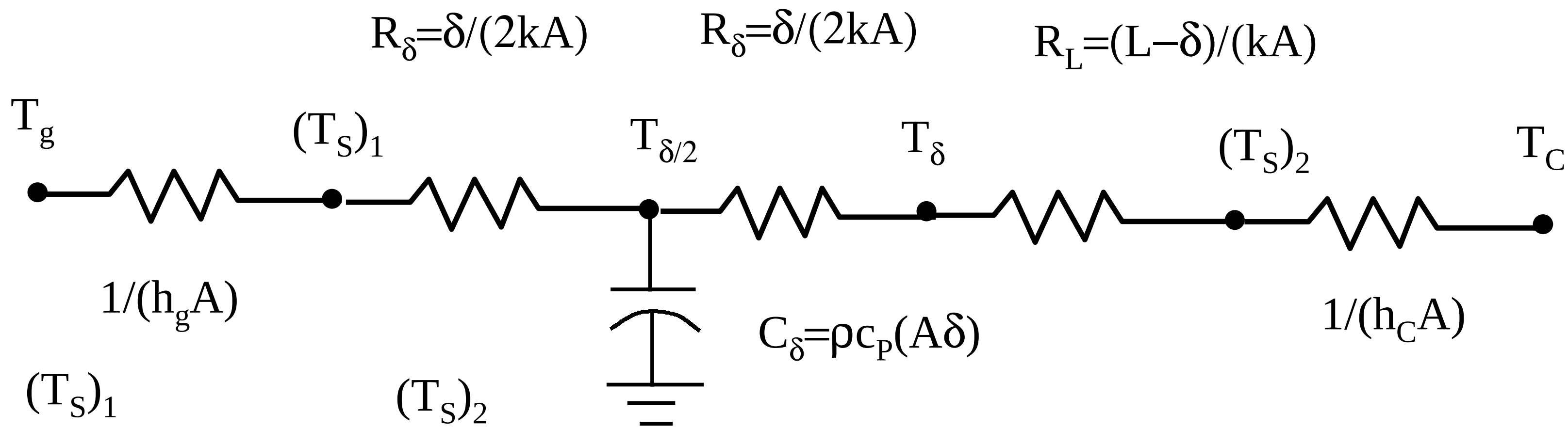
Can be treated as steady state conduction since the temperature oscillation is not significant beyond x=δ

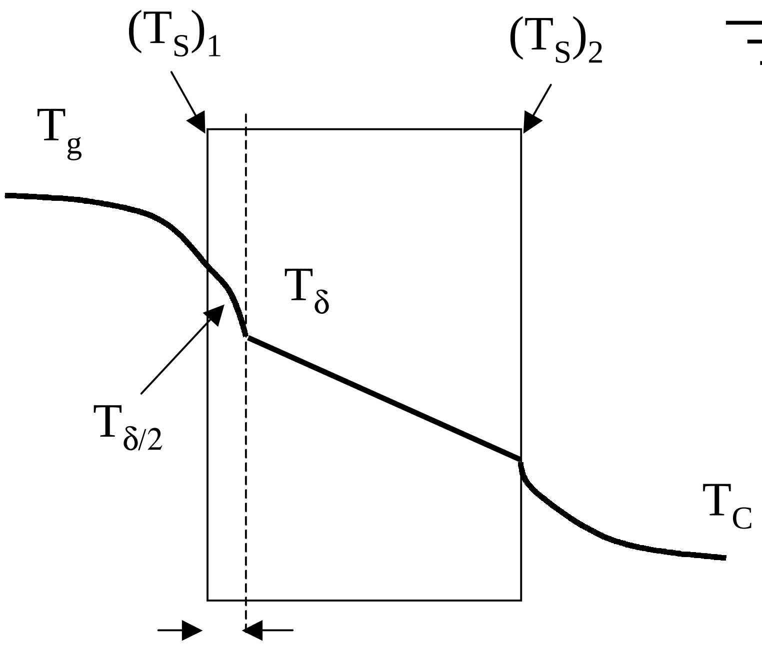
$$\frac{(T_{rms})_{x=\delta}}{(T_{rms})_{x=0}} = 10\%$$

Fluctuating amplitude of the temperature

decays spatially as $\exp\left[-\left(\frac{\omega}{2\alpha}\right)^{1/2} x\right]$

Unsteady Heat Model





δ: penetration depth

$T_{\delta/2}$ is a temperature representative of the temperature inside the penetration layer.