An Overview of Stanford ESP Program

- An engine simulation program for the simulation of the thermodynamics performance of homogeneous charge engines

- Zero dimensional thermodynamic analysis
  - energy and mass balance
  - turbulent modeling
  - two zones flame propagation plus ignition analysis

- Fluid Mechanics
  - Isentropic compressible flow for intake and exhaust flow
  - Manifold analysis using method of characteristics

- Heat Transfer
  - heat loss through the walls (two zones model)

Detailed Procedures

➢ Four stage calculation: compression, burn (ignition and flame propagation), expansion, and gas exchange (inlet, exhaust, and overlap).

(1) Compression stage (the same procedures for expansion stage)

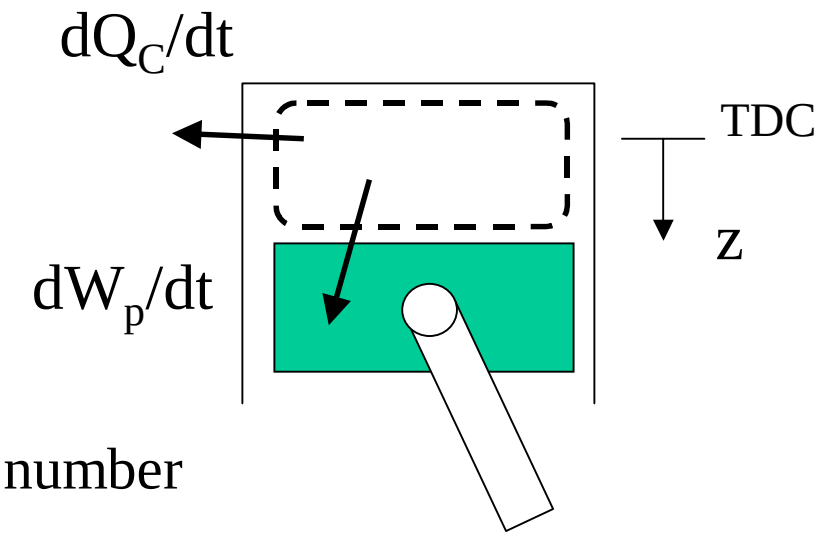
Energy balance:

$$\frac{dU_C}{dt} + \dot{Q}_C + \dot{W}_P = 0 \quad (A)$$

where $\dot{W}_P = PA_P \frac{dz}{dt}$ and

$$\dot{Q}_C = h_C A_C (T_C - T_W)$$

$h_C = St_C \rho c_P V_t$, St_C is the Stanton number



Compression stage (cont.)

- Integrate equation A to advance U_c to the next step. Divided U_c by M_c to obtain the specific internal energy u_c.

- Determine new temperature T_c from u_c (using pre-determined thermodynamic table)

- Calculate specific volume (v) using the new cylinder volume

- Determine pressure using v and T_C using thermodynamic table

- Calculate heat transfer using new T_c. Stanton number is updated using turbulent kinetic energy model (8-35) through the turbulent velocity V_t.

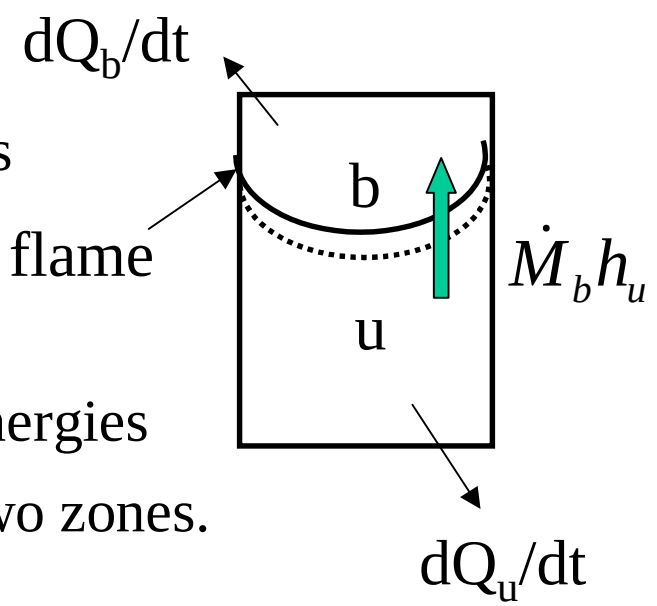
- Repeat until the end of stage

Burn Stage (**ignition** and flame propagation)

- First, the spark ignition stage is a short period between the compression and burn stages at a user-specified crank angle.

- A user-specified mass fraction ($0<f\leq 1$) of reactants convert instantaneously to products.

- Two zones (unburned and burned) are generated at this instant as shown below.



Must satisfy mass and energy conservations

$$M_u + M_b = M_C$$

$$M_u u_u(T_u) + M_b u_b(T_b) = U_C \quad \text{(B)}$$

where u_u and u_b are the specific internal energies and T_u and T_b are the temperatures of the two zones.

Ignition stage

Total volume has to be conserved also:

$M_u v_u(T_u, P_+) + M_b v_b(T_b, P_+) = V_C$ (C)

where v_u and v_b are the specific volumes of the two zones and P_+ is the pressure after ignition.

To determine the pressure and temperature after the ignition, we assume that the unburned gas is undergoing an isentropic compression due to the ignition, that is,

$s_u(T_u, P_+) = s_u(T_-, P_-)$ (D)

where T_- is the unburned gas after ignition, T_- and P_- are the temperature and pressure in the cylinder before ignition. Use equations (B), (C), and (D) to solve for three unknowns: P_+, T_u, and T_b.

Burn Stage (ignition and **flame propagation**)

➢ After ignition, a flame front is generated between the unburned and burned zones. The flame is defined as the thin region where rapid exothermic chemical reaction is taking place. The flame can propagate as a result of strong coupling between chemical reaction, mass and heat diffusions, and fluid flow behavior.

- premixed (spark-ignition) or diffusion (diesel)
- laminar (for low Reynolds number) or turbulent
- steady or unsteady

➢ There will be mass exchange between the two zones and the energy balance can be modeled as:

Unburned zone: $$\frac{dU_u}{dt} + P_C \frac{dV_u}{dt} + \dot{Q}_u + \boxed{\dot{M}_b h_u} = 0$$

Burned zone: $$\frac{dU_b}{dt} + P_C \frac{dV_b}{dt} + \dot{Q}_b = \boxed{\dot{M}_b h_u}$$

Energy transfer due to mass leaving unburned zone

Flame propagation

Mass conservation:

$$\frac{dM_u}{dt} + \dot{M}_b = 0 \quad \text{(E) and } \dot{M}_b = \frac{dM_b}{dt} = -\frac{dM_u}{dt} \quad \text{(F)}$$

This mass exchange is very important since when unburned gases enter the burned zone, the reaction is assumed to be completed (up to a user-specified percentage). Therefore, the enthalpy values for the products will be used instead of the reactants.

The energy equations of two zones can be better presented using the enthaply instead of energy as: H=U+PV.

$$\frac{\mathrm{dH_u}}{\mathrm{dt}} - V_u \frac{dP_C}{dt} + \dot{Q}_u + \dot{M}_b h_u = 0 \quad \text{(G)}$$

$$\frac{\mathrm{dH_b}}{\mathrm{dt}} - V_b \frac{dP_C}{dt} + \dot{Q}_b = \dot{M}_b h_u \quad \text{(H)}$$

Flame propagation

Combining equations (G) & (H) and the ideal gas relation:

h=c_pdT, we can obtain:

$$(V_C - \beta_u V_u - \beta_b V_b)\frac{dP_C}{dt}$$

$$= -P_C \frac{dV_C}{dt} + \beta_b \dot{M}_b (h_u - h_b) - (\beta_u \dot{Q}_u - \beta_b \dot{Q}_b) + \dot{M}_b (\alpha_b - \alpha_u) \quad \text{(I)}$$

where $\beta(T) = \frac{\alpha'}{c_P}$, $\alpha(T) = RT$, $\alpha' = \frac{d\alpha}{dT}$

Equation (I) is used to calculate $\frac{dP_C}{dt}$. With the pressure, equations (G) & (H) can be used to advance the total enthaplies in both zones.

Then equations (E) & (F) will be used to advance the zonal mass balances.

Finally, the new masses and total enthaplies determine the zonal temperatures.

Flame propagation

The new unburned volume is calculated using:

$\frac{V_u}{V_C} = \frac{(MRT)_u}{(MRT)_u + (MRT)_b}$ and the burned volume $V_b = V_C - V_u$.

The pressure is calculated from PV=MRT for whichever zone is larger.

Additional information needed,

Heat losses to the walls: (Unburned zone) $\dot{Q}_u = St_u V_{tu} \rho_u c_{pu} A_u (T_u - T_w)$

(Burned zone) $\dot{Q}_b = St_b V_{tb} \rho_b c_{pb} A_b (T_b - T_w)$

Burn rate: $\dot{M}_b = A_f \rho_u V_f$, where V_f is the flame propagation speed relative to the unburned gases. A_f is the flame front area.

$V_f = V_L + C_f V_{tu}$, where V_L is the specified laminar flame speed,

C_f is a specified coefficient, and V_{tu} is the turbulence velocity.

Gas Exchange Stage (Intake and Exhaust)

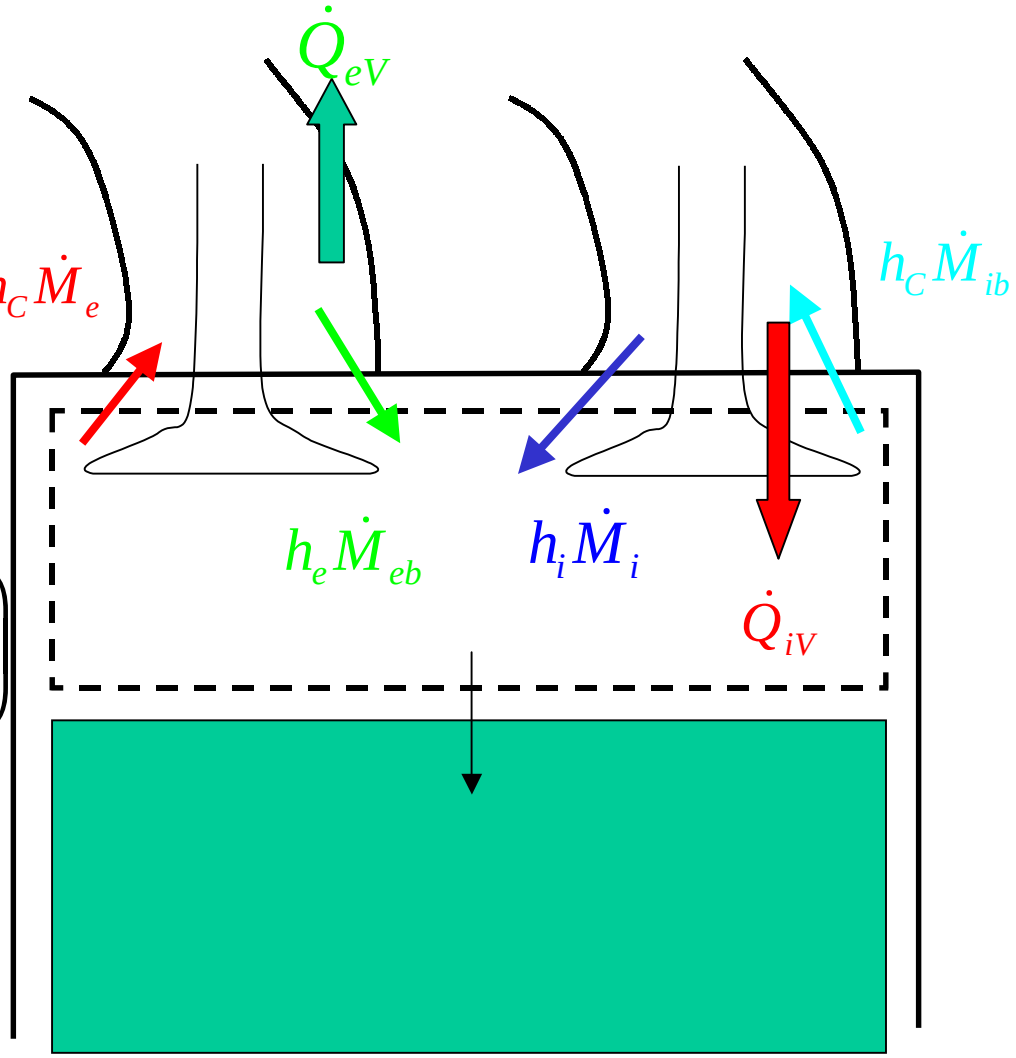
Intake

Backflow into intake

exhaust

Backflow from exhaust

$$\begin{pmatrix} h_i \dot{M}_i - \dot{Q}_{iV} \\ -h_C \dot{M}_{ib} \end{pmatrix} = \frac{dU_C}{dt} + \dot{W}_p + \dot{Q}_C + \begin{pmatrix} h_C \dot{M}_e \\ -h_e \dot{M}_{eb} + \dot{Q}_{eV} \end{pmatrix}$$



$\dot{M} = C_d F(A, \rho, P, P_b, \gamma)$:

C_d is the specified discharge coefficient, F is the isentropic flow rate.