Engines

Exercise III: Energy and exergy balance of a Diesel engine

Solutions:

Preliminary computations:

Expression of the Air / Fuel ratio of the mixture $R_{A/F}$:

$$\frac{N_A}{M_F} = \frac{\lambda}{0.21} \cdot \frac{N_{O2,st}}{M_F} = \frac{\lambda}{0.21} \cdot \left(\frac{c_C^F}{\widetilde{m}_C} + 0.5 \cdot \frac{c_{H2}^F}{\widetilde{m}_{H2}} + \frac{c_S^F}{\widetilde{m}_S} - \frac{c_{O2}^F}{\widetilde{m}_{O2}} \right) = 0.5977\ kmolA/kgF$$

$$R_{A/F} = \frac{M_A}{M_F} = \frac{N_A}{M_F} \cdot \widetilde{m}_A = 17.24\ kgA/kgF$$

1) **Energy balance of the system (F):** $\dot{E}_e^- = \dot{Y}_{comb}^+ - \dot{Q}_G^- - \dot{Q}_{ae}^- - \dot{Q}_{ah}^- - \dot{Q}_{ac}^-$

Heat rate losses of the exhaust gases: $\dot{Q}_G^- = \dot{M}_G \cdot \hat{h}_G + \sum \dot{M}_{iI} \cdot \Delta h_{iI}^0$

with $\hat{h}_G = c_{p,G} \cdot \left(\hat{T}_{G2} - \hat{T}^0 \right) = 630\ kJ/kg$

$$\bar{c}_{p,G}\left(\lambda = 1.2; \hat{T}_{G2} = 550°C \right) = 1200\ J/kgK$$

Conservation of mass (mass balance) $\dot{M}_G = \dot{M}_A + \dot{M}_F = 0.10707\ kg/s$

$$\dot{M}_A = R_{AF} \cdot \dot{M}_F = 0.1012\ kg/s$$

Only the carbon monoxide is unburned, so: $\sum \dot{M}_{iI} \cdot \Delta h_{iI}^0 = \dot{M}_{CO} \cdot \Delta h_{CO}^0$

$$\dot{Q}_G^- = 0.10707 \cdot 630 + 0.000258 \cdot 10100 = 70.1\ kW$$

Heat rate losses of the cooling water network: $\dot{Q}_{ae}^- = \dot{M}_e \cdot c_{p,e} \cdot \left(\hat{T}_{e2} - \hat{T}_{e1} \right)$

$$\dot{Q}_{ae}^- = 50.8\ kW$$

Heat rate losses of the lubricating oil network: $\dot{Q}_{ah}^- = \dot{M}_h \cdot c_{p,h} \cdot \left(\hat{T}_{h2} - \hat{T}_{h1} \right)$

$$\dot{Q}_{ah}^- = 6.9\ kW$$

Fuel transformation power: $\dot{Y}_{comb}^+ = \dot{M}_F \cdot \Delta h_i^0 + \hat{\dot{Y}}_i^+$

where $\hat{\dot{Y}}_i^+$ is the relative fuel transformation power given by:

$$\hat{\dot{Y}}_i^+ = \dot{M}_{cond} \cdot q_{vap}^0 + \left(\dot{M}_F \cdot \hat{h}_F + \dot{M}_A \cdot \hat{h}_A - \dot{M}_G \cdot \hat{h}_G \right)$$

As atmospheric state is equal to standard state, the second term of the right member is equal to:

$$\left(\dot{M}_F \cdot \hat{h}_F + \dot{M}_A \cdot \hat{h}_A - \dot{M}_G \cdot \hat{h}_G \right) = 0$$

Then, considering the hypothesis, we have finally: $\hat{\dot{Y}}_i^+ = \dot{M}_{cond} \cdot q_{vap}^0 = 0$

So finally, transformation power is equal to: $\dot{Y}^{+}_{comb} = \dot{M}_F \cdot \Delta h_i^0$

$$\dot{Y}^{+}_{comb} = 250\ kW$$

Heat rate deperdition by convection / radiation: $\dot{Q}^{-}_{ac} = \dot{Y}^{+}_{comb} - \dot{Q}^{-}_{G} - \dot{Q}^{-}_{ae} - \dot{Q}^{-}_{ah} - \dot{E}^{-}_{e}$

$$\dot{Q}^{-}_{ac} = 22.3\ kW$$

Finally, the energy balance computation is equal to:

Terms:	**Output**	**Input**
Mechanical power	$\dot{E}^{-}_{e} = 100\ kW$	$\dot{Y}^{+}_{comb} = 250\ kW$
Heat rate losses of the exhaust gases	$\dot{Q}^{-}_{G} = 70.1\ kW$	
Heat rate losses of the cooling water	$\dot{Q}^{-}_{ae} = 50.8\ kW$	
Heat rate losses of the lubricating oil	$\dot{Q}^{-}_{ah} = 6.9\ kW$	
Heat rate deperdition due to conv. / rad.	$\dot{Q}^{-}_{ac} = 22.3\ kW$	
Total	$Total = 250\ kW$	$Total = 250\ kW$

2) Energy balance of the system (Boundary F): $\dot{E}^{-}_{e} = \dot{Y}^{+}_{comb} - \dot{Q}^{-}_{G} - \dot{Q}^{-}_{ae} - \dot{Q}^{-}_{ah} - \dot{Q}^{-}_{ac}$

Effectiveness of the system (Boundary F): $\varepsilon = \dfrac{\dot{E}^{-}_{e}}{\dot{Y}^{+}_{comb}} = 1 - \dfrac{\dot{Q}^{-}_{G} + \dot{Q}^{-}_{ae} + \dot{Q}^{-}_{ah} + \dot{Q}^{-}_{ac}}{\dot{M}_F \cdot \Delta h_i^0}$

Finally, the global effectiveness of the system F is equal to:

$$\varepsilon = 40\ \%$$

Optional:

Exergy balance of the system (Boundary F): $\dot{E}^{-}_{e} = \dot{E}^{+}_{y,comb} - \dot{L}$

with $\dot{E}^{+}_{y,comb} = \dot{M}_F \cdot \Delta k^0$

Exergy efficiency of the system (Boundary F): $\eta = \dfrac{\dot{E}^{-}_{e}}{\dot{M}_F \cdot \Delta k^0} = 1 - \dfrac{\dot{L}}{\dot{M}_F \cdot \Delta k^0}$

Which gives a exergy efficiency of: $\eta = 37.9\ \%$

3) Energy balance of the engine (Boundary F_M) : $\dot{E}_e^- + \dot{Y}_{ae}^- + \dot{Y}_{ah}^- = \dot{Y}_{combM}^+ - \dot{Q}_{ac}^-$

Transformation power of the cooling water network: $\dot{Y}_{ae}^- = \dot{Q}_{ae}^-$

$$\dot{Y}_{ae}^- = \dot{M}_e \cdot c_{p,e} \cdot \left(\hat{T}_{e2} - \hat{T}_{e1}\right) = 50.8\ kW$$

Transformation power of the lubricating water network: $\dot{Y}_{ah}^- = \dot{Q}_{ah}^-$

$$\dot{Y}_{ah}^- = \dot{M}_h \cdot c_{p,h} \cdot \left(\hat{T}_{h2} - \hat{T}_{h1}\right) = 6.9\ kW$$

Fuel transformation power: $\dot{Y}_{combM}^+ = \dot{M}_F \cdot \Delta h_i^0 - \sum \dot{M}_{iI} \cdot \Delta h_{iI}^0 + \hat{\dot{Y}}_M^+$

where $\hat{\dot{Y}}_M^+$ is the relative fuel transformation power of the subsystem F given by (see question 2):

$$\hat{\dot{Y}}_M^+ = \dot{M}_{cond} \cdot q_{vap}^0 + \left(\dot{M}_F \cdot \hat{h}_F + \dot{M}_A \cdot \hat{h}_A - \dot{M}_G \cdot \hat{h}_G\right)$$

As atmospheric state is equal to standard state and condensation water flow rate is neglected.

Therefore: $\hat{\dot{Y}}_M^+ = -\dot{M}_G \cdot \hat{h}$

and finally: $\dot{Y}_{combM}^+ = \dot{M}_F \cdot \Delta h_i^0 - \dot{M}_{CO} \cdot \Delta h_{CO}^0 - \dot{M}_G \cdot \hat{h}_G$

$$\dot{Y}_{combM}^+ = 180\ kW$$

Heat rate deperdition by convection / radiation: $\dot{Q}_{ac}^- = \dot{Y}_{combM}^+ - \dot{Y}_{ae}^- - \dot{Y}_{ah}^- - \dot{E}_e^-$

$$\dot{Q}_{ac}^- = 22.3\ kW$$

But, keep in mind that a term of the Fuel transformation power is a potential of energy service provided by the system. Therefore, we also have:

Transformation power of the exhaust gases: $\dot{Y}_G^- = \dot{M}_G \cdot \hat{h}_G = 67.5\ kW$

Effectiveness of the engine (Boundary F_M) :

$$\varepsilon_M = \frac{\dot{E}_e^- + \dot{Y}_G^- + \dot{Y}_{ae}^- + \dot{Y}_{ah}^-}{\dot{M}_F \cdot \Delta h_i^0 - \dot{M}_{CO} \cdot \Delta h_{CO}^0} = \frac{100 + 67.5 + 50.8 + 6.9}{250 - 2.6}$$

Finally, the global effectiveness of the system F_M is equal to: $\varepsilon_M = 91.0\ \%$

Optional:

Exergy balance of the engine (Boundary F_M) : $\dot{E}_e^- + \dot{E}_{yae}^- + \dot{E}_{yah}^- = \dot{E}_{y,combM}^+ - \dot{L}_M$

Considering the following relations:

$$\dot{E}_{y,combM}^+ = \dot{M}_F \cdot \Delta k^0 - \dot{M}_{CO} \cdot \Delta k_{CO}^0 - \dot{M}_G \cdot \Delta\hat{k}_{G2}$$

$$\dot{E}_{yae}^- = \dot{M}_e \cdot \left(k_{e2} - k_{e1}\right)$$

$$\dot{E}_{yah}^- = \dot{M}_e \cdot \left(k_{h2} - k_{h1}\right)$$

Exergy transformation of the exhaust gases:

Calculation of exergy value of the exhaust gases:

$$\hat{k}_{G2} = \hat{h}_G - T_a \hat{s}_G = \hat{h}_G - T_a \cdot c_G \cdot \ln\left(\frac{T_G}{T_a}\right) = 266.7\ kJ/kg$$

Finally, $\dot{M}_G \cdot \hat{k}_{G2} = 28.6\ kW$

Fuel exergy transformation:

$$\dot{E}_{y,combM}^+ = \dot{M}_F \cdot \Delta k^0 - \dot{M}_{CO} \cdot \Delta k_{CO}^0 - \dot{M}_G \cdot \Delta\hat{k}_{G2} = 233\ kW$$

Exergy transformation of the water cooling network: $\dot{E}_{yae}^-$

Calculation of exergy value of the water cooling network:

$$\hat{k}_{e1} = \hat{h}_{e1} - T_a \hat{s}_{e1} = c_e \cdot \left(\hat{T}_{e1} - \hat{T}^0\right) - T_a \cdot c_e \cdot \ln\left(\frac{T_{e1}}{T_a}\right) = 22.4\ kJ/kg$$

$$\hat{k}_{e2} = \hat{h}_{e2} - T_a \hat{s}_{e2} = c_e \cdot \left(\hat{T}_{e2} - \hat{T}^0\right) - T_a \cdot c_e \cdot \ln\left(\frac{T_{e2}}{T_a}\right) = 26.04\ kJ/kg$$

Finally, $\dot{E}_{yae}^- = 8.8\ kW$

Exergy transformation of the lubricating oil network: $\dot{E}_{yah}^-$

Calculation of exergy value of the lubricating oil network:

$$\hat{k}_{h1} = \hat{h}_{h1} - T_a \hat{s}_{h1} = c_h \cdot \left(\hat{T}_{h1} - \hat{T}^0\right) - T_a \cdot c_h \cdot \ln\left(\frac{T_{h1}}{T_a}\right) = 11.16\ kJ/kg$$

$$\hat{k}_{h2} = \hat{h}_{h2} - T_a \hat{s}_{h2} = c_h \cdot \left(\hat{T}_{h2} - \hat{T}^0\right) - T_a \cdot c_h \cdot \ln\left(\frac{T_{h2}}{T_a}\right) = 14.58\ kJ/kg$$

Finally, $\dot{E}_{yah}^- = 1.30\ kW$

Exergy loss (according exergy balance): $\dot{L}_M = \dot{E}^+_{y,combM} - \dot{E}^-_e - \dot{E}^-_{yae} - \dot{E}^-_{yah}$

$$\dot{L}_M = 233 - 100 - 8.8 - 1.3 = 122.9\ kW$$

Exergy efficiency of the engine (Boundary F_M): $\eta_M = \dfrac{\dot{E}^-_e + \dot{M}_G \cdot \hat{k}_{G2} + \dot{E}^-_{yae} + \dot{E}^-_{yah}}{\dot{M}_F \cdot \Delta k^0 - \dot{M}_{CO} \cdot \Delta k^0_{CO}}$

Numerical application: $\eta_M = \dfrac{100 + 28.6 + 8.8 + 1.3}{264.1 - 2.54}$

Which gives an exergy efficiency: $\eta_M = 53.0\ \%$

4) If the unburned hydrocarbons are considered as part of the energy losses, the engine effectiveness is:

$$\varepsilon'_M = \frac{\dot{E}^-_e + \dot{Y}^-_G + \dot{Y}^-_{ae} + \dot{Y}^-_{ah}}{\dot{M}_F \cdot \Delta h^0_i} = 90.0\ \%$$

Optional:

And the exergy efficiency is equal to:

$$\eta'_M = \frac{\dot{E}^-_e + \dot{M}_G \cdot \hat{k}_{G2} + \dot{E}^-_{yae} + \dot{E}^-_{yah}}{\dot{M}_F \cdot \Delta k^0} = 52.5\ \%$$