UCL Mechanical Engineering 2021/2022
MECH0024 Thermodynamics Coursework

RFLH9

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1 Question 1

1.1 Solar power available

At the time of measurement, the orbital characteristics are as follows.

Solar declination:

$$\theta_d = -12° \tag{1.1}$$

Polar angle at latitude 51.5°:

$$\theta = 90 - 51.5 = 38.5° \tag{1.2}$$

Hour angle at 11am:

$$\phi = \frac{11 \cdot 360}{24} - 90 = 75° \tag{1.3}$$

Solar azimuth angle:

$$\cos\psi = \cos\theta_d \sin\theta \sin\phi + \sin\theta_d \cos\theta \tag{1.4}$$

$$\psi = \arccos\left[\cos(-12)\sin(38.5)\sin(75) + \sin(-12)\cos(38.5)\right] \tag{1.5}$$

$$\psi = 64.82° \text{ or} \tag{1.6}$$

$$\cos\psi = 0.43; \tag{1.7}$$

Air mass ratio:

$$M = \sec\psi \tag{1.8}$$

$$M = 2.35 \tag{1.9}$$

Solar flux:

$$E = 1353\left(0.057 + 0.83e^{-0.5M}\right)\,\mathrm{kW\,m^{-2}} \tag{1.10}$$

$$E = 220.18\,\mathrm{kW\,m^{-2}} \tag{1.11}$$

The orbital characteristics for when the solar panels are orientated normal to the sun's rays are as follows:

Solar declination, θ_d	$-5°$
Polar angle, θ	38.5°
Hour angle, ϕ	90°

Table 1: Orbital characteristics when panels are normal to sun's rays.

Therefore:

$$\theta + \theta_d + \alpha = \phi \tag{1.12}$$

$$38.5 - 5 + \alpha = 90 \tag{1.13}$$

$$\alpha = 56.5° \tag{1.14}$$

Intensity of radiation for collector inclined at α degrees to normal:

$$E_\alpha = E\left[\cos\theta_d \sin(\theta+\alpha)\sin\phi + \sin\theta_d \cos(\theta+\alpha)\right] E_\alpha = 211.23\,\mathrm{W\,m^{-2}} \tag{1.15}$$

Area of collectors (A_p) is $920\,\mathrm{m}^2$, therefore intensity of radiation for total collector area is:

$$\text{Incident solar energy} = 211.23 \cdot 920 \cdot 10^{-3} = 194.33\,\mathrm{kW} \tag{1.16}$$

Looking at the sources of lost energy in our system, we have energy lost due to convection to atmosphere and re-radiated energy. We also have the heat transfer to the working fluid. This must equal the energy in, which is equal to the incident solar energy multiplied by the absorptivity of the collector surface.

Energy absorbed by the collector:

$$\theta_{solar} = \text{incident solar energy} \cdot A \tag{1.17}$$

where A is absorptivity of the collector surface.

Convection to atmosphere:

$$\theta_{conv} = A_p h \left(T_s - T_a\right) \tag{1.18}$$

where where A_p is area of collector, h is convective heat transfer coefficient between the collector surface and the surrounding air, T_s is average temperature of collector surface, T_a is the temperature of the surrounding air.

Re-radiated energy:

$$\theta_{rad} = A_p \varepsilon \sigma \left(T_s^4\right) \tag{1.19}$$

where ε is emissivity of collector surface, σ is Stefan-Boltzmann constant.

The above constants are given in the question. MATLAB was used to calculate the solar power available at the collectors following losses:

```
clc
clear
close all

%at measurement time
thetaD = -12*(pi/180);
lati = 51.5;
theta = (90-lati)*(pi/180);
timeOfDay = 11;
phi = ((timeOfDay*360)/24 - 90)*(pi/180);

cosPsi = (cos(thetaD))*(sin(theta))*(sin(phi))+(sin(thetaD))*(cos(theta));
psi = acos(cosPsi);
M = sec(psi);
E = 1353*(0.027+0.81*exp(-0.76*M));

%angles where collector is orientated normal
thetaDNorm = (-5)*(pi/180);
latiNorm = 51.5;
thetaNorm = (90 - latiNorm)*(pi/180);
timeOfDayNorm = 12;
phiNorm = ((timeOfDayNorm*360)/24 - 90)*(pi/180);
alpha = phiNorm - thetaDNorm - thetaNorm;

EAlpha = E
    *(cos(thetaD)*sin(theta+alpha)*sin(phi) + sin(thetaD)*cos(theta + alpha));
Area = 920;
IncEnergy = EAlpha*Area;

%losses
absorp = 0.97;
epsi = 0.0941;
sigma = 5.67e-11;
TA = 8+273.15;
```

```
TS = 45+273.15;
h = 0.00256;

%energy bal
thetaSolar = IncEnergy*absorp;
thetaConv = Area*h*(TS - TA);
thetaRad = Area*epsi*sigma*(TS^4);
powerAvail = thetaSolar - thetaConv - thetaRad;
```

Here we can see that our final answer is stored in the variable `powerAvail`:

$$\texttt{powerAvail} = 188.361\,\mathrm{kW} \tag{1.20}$$

1.2 Viability of proposed provision

2 Question 2

2.1 a

2.1.1 Irreversibility associated with increase in steady flow exergy of steam

2.1.2 Maximum theoretical work available

2.2 Relative advantages and disadvantages of four primary energy sources utilised in thermal power generation

3 Question 3

3.1 a

3.1.1 Mass of methane present

3.1.2 Approximate level of CO in exhaust gases

3.2 Effects of fuel molecular composition on ignition, temperatures and formation of exhaust pollutants during combustion

4 Question 4

4.1 a

4.1.1 Ideal operating voltage

Applying steady flow energy equation

$$\dot{Q} - \dot{W} = \dot{m}\left(h_{P0} - h_{R0}\right) \tag{4.1}$$

where $\dot{Q}$ is our heat loss, $\dot{W}$ is our work done, $\dot{m}$ is the mass flow rate, h_{P0} is enthalpy of products and h_{R0} is enthalpy of reactants.

Since we are considering an ideal fuel cell, we can utilise the following:

$$\dot{Q} = \dot{m}T_0\left(s_{P0} - s_{R0}\right) \tag{4.2}$$

Therefore:

$$\dot{W} = \dot{m}T_0\left(s_{P0} - s_{R0}\right) - \dot{m}\left(h_{P0} - h_{R0}\right) \tag{4.3}$$

$$\dot{W} = \dot{m}\left[\left(h_{R0} - T_0 s_{R0}\right) - \left(h_{P0} - T_0 s_{P0}\right)\right] \tag{4.4}$$

We know that:

$$\text{Gibbs function} = h - Ts \tag{4.5}$$

Therefore:

$$\dot{W} = -\dot{m}\Delta G \tag{4.6}$$

In this case:

$$45 = -\dot{m}\left(-226500\right) \tag{4.7}$$

$$\dot{m} = \frac{45}{226500} = 1.99 \times 10^{-4}\,\mathrm{kmol\,s^{-1}} \tag{4.8}$$

We also know:

$$\dot{W} = V\mathcal{F}n\dot{m} \tag{4.9}$$

where V is the ideal operating voltage, $\mathcal{F}$ is Faraday's constant and n is number of charge transfers per molecule of fuel. Hence:

$$V = \frac{\dot{W}}{\mathcal{F}n\dot{m}} \tag{4.10}$$

$$V = \frac{45 \cdot 226500}{96485 \cdot 2 \cdot 45} = 1.1738\,\mathrm{V} \tag{4.11}$$

4.1.2 Anode area

We know that:

$$P = IV \tag{4.12}$$

$$I = \frac{45000}{1.1738} = 38\,338\,\mathrm{A} \tag{4.13}$$

Therefore, the anode area necessary is:

$$\text{Anode area} = \frac{38338}{6500} = 5.8982\,\mathrm{m}^2 \tag{4.14}$$

4.1.3 Heat loss

Applying steady flow energy equation (subscript a denotes 'actual'):

$$\dot{Q}_a - \dot{W}_a = \dot{m}\Delta H \tag{4.15}$$

$$\dot{Q}_a = \dot{m}\Delta H + 2 \cdot \dot{m}\mathcal{F}V_a \tag{4.16}$$

$$\dot{Q}_a = \frac{45}{226500}\left(-239800 \cdot 10^3 + 2 \cdot 96.485 \cdot 10^6 \cdot 0.984\right) \tag{4.17}$$

$$\dot{Q} = -9.92\,\mathrm{kW} \tag{4.18}$$

4.2 Limitations of hydrogen oxygen fuel cell vehicles