UCL Mechanical Engineering 2020/2021

MECH0011 Final Coursework

NCWT3

May 19, 2021

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1 Question 1

1.1 a

The data was imported into MATLAB and the shape of the hydrofoil, the chord line and the mean camber line were plotted for all four hydrofoils.

```
clc
clear
close all

%define vars
i = ["EPPLER 818 Hydrofoil", "NACA 63-412 Aifoil", "RG 8 Airfoil", "YS 930 Hydrofoil"]; %index hydrofoil names from sheets for ease
data = zeros(122,2,4); %initialise matrix
counter = 0; %initialise counter
x = linspace(0,1,100); %interpolation range initialisation

%import data
for j = 1:4 %index all data for plots
    counter = counter + 1; %increment counter
    data(:,:,counter) = readmatrix('suppFiles.xlsx','Sheet',i(j),'Range','A3:B124'); %loop through sheets and pull data
end

%camber line calculation
%pull positive and negative coordinate points
%eppler
dataPos1 = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','A3:B37');
dataNeg1 = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','A38:B70');

%naca
dataPos2 = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','A3:B28');
dataNeg2 = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','A29:B54');

%rg
```

```
dataPos3 = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','A3:B34');
dataNeg3 = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','A35:B64');

%ys
dataPos4 = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','A3:B65');
dataNeg4 = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','A66:B124');

%interpolate hydrofoil shape with 100 data points from 0 to 1
%eppler
dataIntPos1 = interp1(dataPos1(:,1), dataPos1(:,2), x);
dataIntNeg1 = interp1(dataNeg1(:,1), dataNeg1(:,2), x);

%naca
dataIntPos2 = interp1(dataPos2(:,1), dataPos2(:,2), x);
dataIntNeg2 = interp1(dataNeg2(:,1), dataNeg2(:,2), x);

%rg
dataIntPos3 = interp1(dataPos3(:,1), dataPos3(:,2), x);
dataIntNeg3 = interp1(dataNeg3(:,1), dataNeg3(:,2), x);

%ys
dataIntPos4 = interp1(dataPos4(:,1), dataPos4(:,2), x);
dataIntNeg4 = interp1(dataNeg4(:,1), dataNeg4(:,2), x);

%calculate camber line
%eppler
camber1 = (dataIntPos1 + dataIntNeg1)./2;

%naca
camber2 = (dataIntPos2 + dataIntNeg2)./2;

%rg
camber3 = (dataIntPos3 + dataIntNeg3)./2;

%ys
camber4 = (dataIntPos4 + dataIntNeg4)./2;

%plot data
subplot(4,1,1)
plot(dataPos1(:,1), dataPos1(:,2),'b',dataNeg1(:,1), dataNeg1(:,2),'b', x
    , camber1, 'r')
axis image
grid on
xlabel('Chord')
ylabel('Z(x)')
title('Plot of ' + i(1))
xlim([-0.05 1.05])
ylim([-0.05 0.1])
legend('Hydrofoil profile','Mean camber line')

subplot(4,1,2)
plot(dataPos2(:,1), dataPos2(:,2),'b',dataNeg2(:,1), dataNeg2(:,2),'b', x
    , camber2, 'r')
```

```
axis image
grid on
xlabel('Chord')
ylabel('Z(x)')
title('Plot of ' + i(2))
xlim([-0.05 1.05])
ylim([-0.05 0.1])
legend('Hydrofoil profile','Mean camber line')

subplot(4,1,3)
plot(dataPos3(:,1), dataPos3(:,2),'b',dataNeg3(:,1), dataNeg3(:,2),'b', x
    , camber3,'r')
axis image
grid on
xlabel('Chord')
ylabel('Z(x)')
title('Plot of ' + i(3))
xlim([-0.05 1.05])
ylim([-0.05 0.1])
legend('Hydrofoil profile','Mean camber line')

subplot(4,1,4)
plot(dataPos4(:,1), dataPos4(:,2),'b',dataNeg4(:,1), dataNeg4(:,2),'b', x
    , camber4,'r')
axis image
grid on
xlabel('Chord')
ylabel('Z(x)')
title('Plot of ' + i(4))
xlim([-0.05 1.05])
ylim([-0.05 0.1])
legend('Hydrofoil profile','Mean camber line')
```

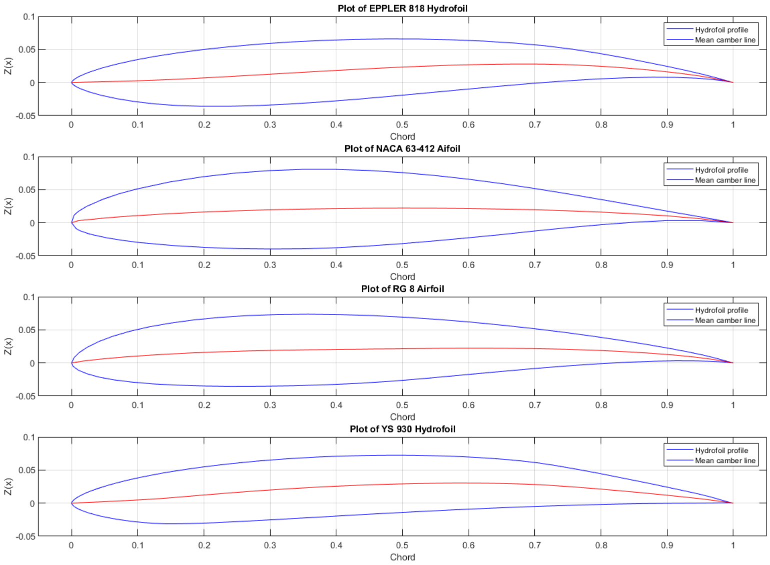

Figure 1: Graphs to show hydrofoil shape, chord line and mean camber line for four different hydrofoils.

1.2 b

MATLAB was used to calculate the lift-to-drag ratio for each hydrofoil.

```
clc
clear
close all

%define vars
i = ["EPPLER 818 Hydrofoil", "NACA 63−412 Aifoil", "RG 8 Airfoil", "YS 930 Hydrofoil"]; %index hydrofoil names from sheets for ease

%pull cl and cd from data
%eppler
epplerCL = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','E2:E79');
epplerCD = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','F2:F79');

%naca
nacaCL = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','E2:E107');
nacaCD = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','F2:F107');

%rg
rgCL = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','E2:E101');
rgCD = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','F2:F101');

%ys
ysCL = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','E2:E78');
ysCD = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','F2:F78');

%plot data
```

```
plot(epplerCL, epplerCD, 'r', nacaCL, nacaCD, 'g', rgCL, rgCD, 'b', ysCL, ysCD, '
    magenta')
legend(i(1), i(2), i(3), i(4))
axis square
grid on
xlabel('C_L')
ylabel('C_D')
title('Plot of lift-to-drag ratio for ' + i(4))
```

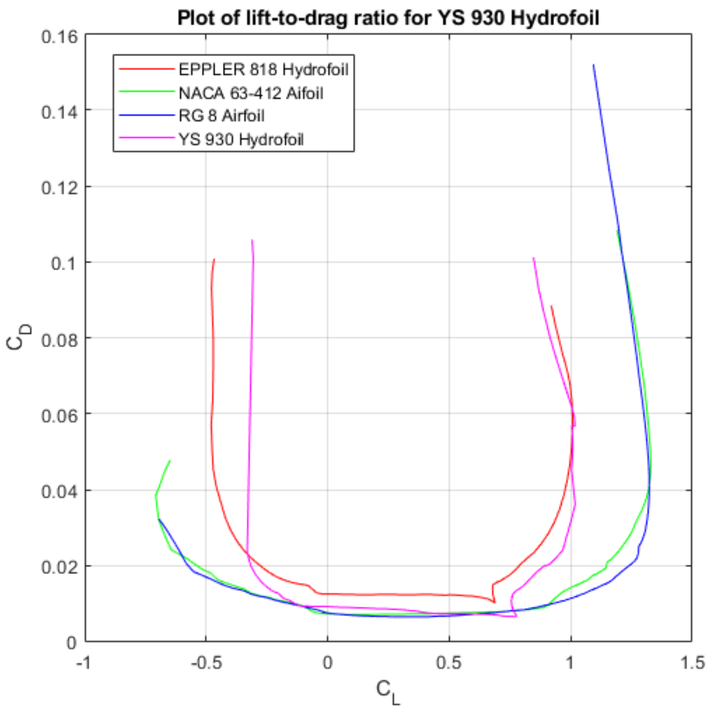

Figure 2: Graph to show lift-to-drag ratio for four different hydrofoils.

1.3 c

At a low angle of attack, the flow is attached to the hydrofoil and separates close to the trailing edge, leaving a small wake. The streamlined shape of the hydrofoil exerts a large shear force on the flow passing over it, leading to a large skin drag but low form drag. As we increase the angle of attack, the flow separation moves along the top of the hydrofoil. This decreases the shear force acting on the hydrofoil and the skin drag starts to reduce, with form drag increasing. At the stall angle, the pressure distribution along the top of the hydrofoil dramatically changes due to flow separation, suction pressure is mostly/all lost and a large wake with turbulent effects is present. The primary drag effect here is now form drag, as the flow is not attached along the length of the hydrofoil surface.

1.4 d

MATLAB was used to calculate each of the variables for each hydrofoil.

```
clc
clear
```

```
close all

%define vars
i = ["EPPLER 818 Hydrofoil", "NACA 63-412 Aifoil", "RG 8 Airfoil", "YS 930 Hydrofoil"]; %index hydrofoil names from sheets for ease
x = linspace(0,1,100); %interpolation range initialisation

%max percentage camber line calculation
%camber line calculation
%pull positive and negative coordinate points
%eppler
dataPos1 = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','A3:B37');
dataNeg1 = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','A38:B70');

%naca
dataPos2 = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','A3:B28');
dataNeg2 = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','A29:B54');

%rg
dataPos3 = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','A3:B34');
dataNeg3 = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','A35:B64');

%ys
dataPos4 = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','A3:B65');
dataNeg4 = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','A66:B124');

%interpolate hydrofoil shape with 100 data points from 0 to 1
%eppler
dataIntPos1 = interp1(dataPos1(:,1), dataPos1(:,2), x);
dataIntNeg1 = interp1(dataNeg1(:,1), dataNeg1(:,2), x);

%naca
dataIntPos2 = interp1(dataPos2(:,1), dataPos2(:,2), x);
dataIntNeg2 = interp1(dataNeg2(:,1), dataNeg2(:,2), x);

%rg
dataIntPos3 = interp1(dataPos3(:,1), dataPos3(:,2), x);
dataIntNeg3 = interp1(dataNeg3(:,1), dataNeg3(:,2), x);

%ys
dataIntPos4 = interp1(dataPos4(:,1), dataPos4(:,2), x);
dataIntNeg4 = interp1(dataNeg4(:,1), dataNeg4(:,2), x);

%calculate camber line
%eppler
camber1 = (dataIntPos1 + dataIntNeg1)./2;

%naca
camber2 = (dataIntPos2 + dataIntNeg2)./2;

%rg
camber3 = (dataIntPos3 + dataIntNeg3)./2;
```

```
%ys
camber4 = (dataIntPos4 + dataIntNeg4)./2;

%maximum camber per hydrofoil
%eppler
percCamber1 = max(camber1);

%naca
percCamber2 = max(camber2);

%rg
percCamber3 = max(camber3);

%ys
percCamber4 = max(camber4);

%clean-up output
percCamber = 100.*[percCamber1 percCamber2 percCamber3 percCamber4];

%maximum percentage thickness calculation
%eppler
thickness1 = (abs(dataIntPos1) + abs(dataIntNeg1));

%naca
thickness2 = (abs(dataIntPos2) + abs(dataIntNeg2));

%rg
thickness3 = (abs(dataIntPos3) + abs(dataIntNeg3));

%ys
thickness4 = (abs(dataIntPos4) + abs(dataIntNeg4));

%max thickness per hydrofoil
%eppler
maxThick1 = max(thickness1);

%naca
maxThick2 = max(thickness2);

%rg
maxThick3 = max(thickness3);

%ys
maxThick4 = max(thickness4);

%clean-up output
maxThick = 100.*[maxThick1 maxThick2 maxThick3 maxThick4];

%maximum lift coefficient
%pull angle of attack, cl and cd from data
%eppler
epplerData = readmatrix('suppFiles.xlsx','Sheet',i(1),'Range','D2:F79');

```

```
%naca
nacaData = readmatrix('suppFiles.xlsx','Sheet',i(2),'Range','D2:F107');

%rg
rgData = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','D2:F101');

%ys
ysData = readmatrix('suppFiles.xlsx','Sheet',i(4),'Range','D2:F78');

%find max cl
%eppler
maxEpplerCL = max(epplerData(:,2));

%naca
maxNacaCL = max(nacaData(:,2));

%rg
maxRgCL = max(rgData(:,2));

%ys
maxYsCL = max(ysData(:,2));

%clean-up output
maxCL = [maxEpplerCL maxNacaCL maxRgCL maxYsCL];

%find angle of attack at max cl
%eppler
critEppler = epplerData(epplerData(:,2) == maxEpplerCL,1);

%naca
critNaca = nacaData(nacaData(:,2) == maxNacaCL,1);

%rg
critRg = rgData(rgData(:,2) == maxRgCL,1);

%ys SPECIAL CASE VALUE ASCERTAINED EMPIRICALLY
critYs = 9;

%clean-up output
crit = [critEppler critNaca critRg critYs];

%lift coefficient for alpha = 0
%eppler
liftAlpha0Eppler = epplerData(epplerData(:,1) == 0,2);

%naca
liftAlpha0Naca = nacaData(nacaData(:,1) == 0,2);

%rg
liftAlpha0Rg = rgData(rgData(:,1) == 0,2);

%ys
liftAlpha0Ys = ysData(ysData(:,1) == 0,2);
```

```
%clean-up output
liftAlpha0 = [liftAlpha0Eppler liftAlpha0Naca liftAlpha0Rg liftAlpha0Ys];

%angle of attack corresponding to cl = 0
%find min cl
%eppler
minEpplerCL = min(abs(epplerData(:,2)));

%naca
minNacaCL = min(abs(nacaData(:,2)));

%rg
minRgCL = min(abs(rgData(:,2)));

%ys
minYsCL = min(abs(ysData(:,2)));

%find angle of attack at min cl
%eppler
AOAMinEppler = epplerData(epplerData(:,2) == minEpplerCL,1);

%naca
AOAMinNaca = nacaData(nacaData(:,2) == -minNacaCL,1);

%rg
AOAMinRg = rgData(rgData(:,2) == -minRgCL,1);

%ys
AOAMinYs = ysData(ysData(:,2) == -minYsCL,1);

%clean-up output
AOAMin = [AOAMinEppler AOAMinNaca AOAMinRg AOAMinYs];

%generate table
T = table(i', percCamber', maxThick', maxCL', crit', liftAlpha0', AOAMin
    ');
```

	Maximum		
Hydrofoil	% camber	% thickness	lift coefficient
EPPLER 818 Hydrofoil	2.792	9.362	1.008
NACA 63-412 Aifoil	2.204	11.992	1.330
RG 8 Airfoil	2.226	10.795	1.323
YS 930 Hydrofoil	3.028	9.088	1.018

Table 1: Table to show maximum percentage camber and thickness and the maximum lift coefficient for four hydrofoils.

Hydrofoil	Stall angle	Lift coefficient for $\alpha = 0°$	Angle of attack α_0 corresponding to $C_L = 0$
EPPLER 818 Hydrofoil	7.75°	0.361	−3°
NACA 63-412 Aifoil	13°	0.338	−3°
RG 8 Airfoil	12.75°	0.382	−3°
YS 930 Hydrofoil	9°	0.391	−3.75°

Table 2: Table to show the stall angle, lift coefficient for $\alpha = 0°$ and the angle of attack α_0 corresponding to $C_L = 0$ for four hydrofoils.

The hydrofoils both have a higher percentage camber than the airfoils. They also have a lower percentage thickness than the airfoils. We can see that this leads to a reduction in the stall angle and subsequently their maximum lift coefficients are lower. However, we can see that they perform better at $\alpha = 0°$. This can be attributed to the fact that at small α, larger camber generates more lift, at the expense of a smaller stall angle, as the boundary layer is more prone to separation at higher α. However, increasing either percentage camber or thickness will increase C_D.

1.5 e

The RG 8 Airfoil was selected as it has a high stall angle, with a subsequently large maximum lift coefficient, the lift coefficient at $\alpha = 0°$ is also the second highest. We can calculate the lift on the hydrofoil using 1.1:

$$L = \frac{1}{2}\rho C_L V_w^2 A \tag{1.1}$$

where ρ is the density of seawater, C_L is the lift coefficient for a given angle of attack, V_w is the velocity of the fluid relative to the wing and A is the projected surface area of the wing. The surface area A can be found by integration:

$$A = \int_{x_0}^{b+x_0} (-0.07x + c_0)\, \mathrm{d}x \tag{1.2}$$

$$A = \left[-0.035x^2 + c_0 x\right]_{x_o}^{b+x_0} \tag{1.3}$$

$x_0 = 0.1$ as given in the material. I have also selected $b = 2\,\mathrm{m}$, hence:

$$A = -0.035(2.1)^2 + c_0(2.1) + 0.035(0.1)^2 - c_0(0.1) \tag{1.4}$$

$$A = 2c_0 - 0.154 \tag{1.5}$$

Substituting 1.5 into 1.1:

$$L = \frac{1}{2}\rho C_L V_w^2 \left(2c_0 - 0.154\right) \tag{1.6}$$

Rearranging for c_0:

$$(2c_0 - 0.154) = \frac{L}{\frac{1}{2}\rho C_L V_w^2} \tag{1.7}$$

$$c_0 = \frac{L}{\rho C_L V_w^2} + 0.077 \tag{1.8}$$

The following values were used: $\rho = 1036\,\mathrm{kg\,m^{-3}}$ [1], $V_w = 11\,\mathrm{m\,s^{-1}}$ ($39.6\,\mathrm{km\,h^{-1}}$), $L = 2000 \times 9.81 \approx 20\,000\,\mathrm{N}$. MATLAB was used to plot the chord length against the angle of attack. As V_w represents the upper speed limit of the boat, we want to select a low angle of attack, to reduce the amount of drag on the foil. Hence, the value for C_L at $\alpha = 0$ will be used.

```
clc
clear
close all

%define vars
i = ["EPPLER 818 Hydrofoil", "NACA 63-412 Aifoil", "RG 8 Airfoil", "YS
    930 Hydrofoil"]; %index hydrofoil names from sheets for ease
Vw = 11; %39.6km/h
VwLower = 6; %21.6km/h

%pull angle of attack, cl and cd from data
%rg
rgData = readmatrix('suppFiles.xlsx','Sheet',i(3),'Range','D2:F101');

%chord length equation
RGChord = ((20000)./(1036.*(Vw^2).*(rgData(rgData(:,1) == 0,2)))) +
    0.077;%finds CL at alpha = 0 and inputs into equation and solves
L = 0.5.*1036.*(Vw^2).*(rgData(rgData(:,1) == 0,2)).*((2.*RGChord)-0.154)
    ; %check
LLower = 0.5.*1036.*(VwLower^2).*(rgData(rgData(:,1) == 11,2)).*((2.*
    RGChord)-0.154);%alpha = 11 degrees
```

Our chord length is calculated to be $c_0 = 0.4948\,\mathrm{m}$. We must now check whether this chord length is sufficient to lift the boat at lower speeds. In order to do this we require a high angle of attack, to generate more lift. The value for C_L at 11° was used to test the lift at $6\,\mathrm{m\,s^{-1}}$ ($21.6\,\mathrm{km\,h^{-1}}$) and MATLAB gives a lift value of 20 215 N, allowing the boat to be out of the water at lower speeds as well.

2 Question 2

3 Question 3

3.1 a

MATLAB was used to plot the boundary layer velocity profile.

```
clc
clear
close all

%import data
data = readmatrix('suppFiles.xlsx','Sheet','Boundary Layer','Range','A2:
    B102');

%plot data
plot(data(:,2), data(:,1))
axis image
grid on
xlim([0 1])
ylim([0 1])
```

```
xlabel('y/\delta')
ylabel('u/U')
title('Graph to show the boundary layer velocity profile')
```

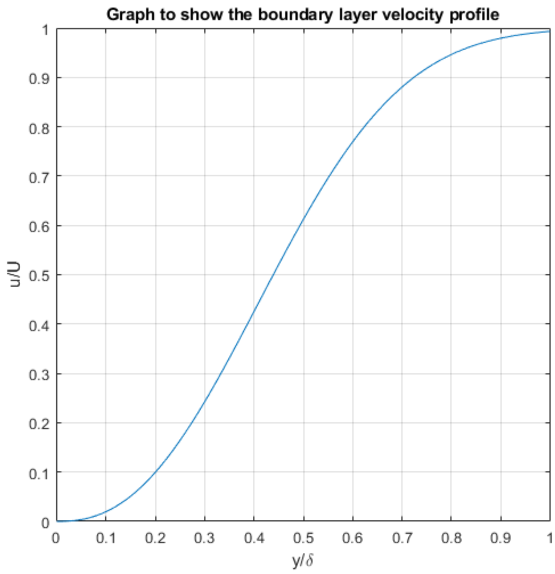

Figure 3: Graph to show boundary layer velocity profile.

4 Question 4

4.1 a

The balanced reaction equation takes the general form:

$$C_xH_y + a\,(O_2 + 3.76\,N_2) \longrightarrow b\ CO_2 + c\ H_2O + 3.76d\ N_2 \tag{4.1}$$

$$CH_4 + a\,(O_2 + 3.76\,N_2) \longrightarrow b\ CO_2 + c\ H_2O + 3.76d\ N_2 \tag{4.2}$$

where $x = 1$ and $y = 4$. Balancing atoms:

$$\mathrm{C} : x = b \tag{4.3}$$

$$\mathrm{H} : y = 2c \tag{4.4}$$

$$\mathrm{O} : 2a = 2b + c \tag{4.5}$$

$$\mathrm{N} : 2 \times 3.76a = 2 \times 3.76d \tag{4.6}$$

$$\therefore a = x + \frac{y}{4} = 2 \tag{4.7}$$

$$b = x = 1 \tag{4.8}$$

$$c = \frac{y}{2} = 2 \tag{4.9}$$

$$d = a = 2 \tag{4.10}$$

Therefore our balanced reaction equation is:

$$CH_4 + 2\,(O_2 + 3.76\,N_2) \longrightarrow CO_2 + 2\,H_2O + 7.52\,N_2 \tag{4.11}$$

4.2 b

The air-fuel ratio on a mass basis can be found using 4.12

$$AF = \bar{AF} \times \frac{M_{air}}{M_{fuel}} \tag{4.12}$$

Where and $\bar{AF}$ is volumetric air ratio and M is the molar mass. Assuming that the air only consists of oxygen and nitrogen, we can input molar masses from the property tables into the 4.12:

$$AF = \frac{2.2\,(1 + 3.76)}{1} \times \frac{\left(\frac{32 + 3.76\,(28.01)}{4.76}\right)}{16.04} \tag{4.13}$$

$$AF = 18.8\,\mathrm{kg_{air}\,kg_{fuel}^{-1}} \tag{4.14}$$

4.3 c

I selected a temperature of 450 K (176.85 °C).

5 Question 5

5.1 a

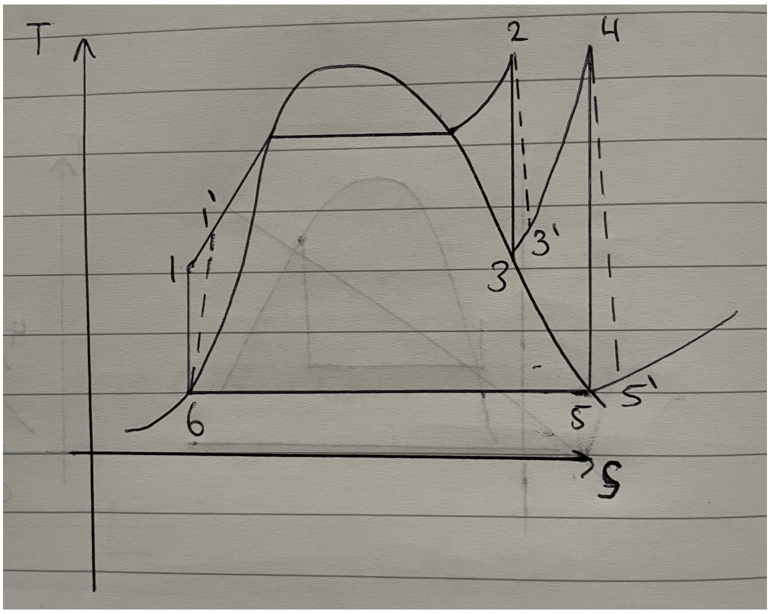

Figure 4: Graph to show Rankine cycle on T-s diagram.

In an ideal Rankine reheat cycle, we would see that the expansion and compression processes are reversible and isentropic. These are shown as straight vertical lines from 6 - 1 (pump compression), 2 - 3 and 4 - 5 (turbine expansion). However, in an actual Rankine reheat cycle, we will have irreversible losses present. For a pump, work must be done to overcome frictional forces. For a turbine, heat transfer from the turbine to the surroundings represents a loss. This process of transfer of energy as work results in entropy being produced within the system, hence we would see the entropy increase for these processes. These have been represented as the curved lines 6 - 1', 2 - 3' and 4 - 5'.

5.2 b

All components in the Rankine reheat cycle are steady flow devices. Neglect kinetic and potential energy changes as they are usually small relative to the work and heat transfer terms. Starting with SFEE formula:

$$\dot{Q}_{in} + \dot{W}_{in} + \dot{m}_1 h_1 = \dot{Q}_{out} + \dot{W}_{out} + \dot{m}_2 h_2 \tag{5.1}$$

$\dot{m}_1 = \dot{m}_2 = \dot{m}$. Dividing by $\dot{m}$:

$$q_{in} + w_{in} + h_1 = q_{out} + w_{out} + h_2 \tag{5.2}$$

The thermal efficiency is given by:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{turbines} - w_{pump}}{q_{in}} \tag{5.3}$$

We know that the total heat input will come from the primary heating stage and the reheating stage, hence:

$$q_{in} = q_{\text{primary}} + q_{\text{reheat}} = (h_2 - h_1) + (h_4 - h_3) \tag{5.4}$$

Total power output from the turbines can be calculated as:

$$w_{turbines} = w_{turb1} + w_{turb2} = (h_2 - h_3) + (h_4 - h_5) \tag{5.5}$$

Pump power can be calculated as:

$$w_{pump} = (h_1 - h_6) \tag{5.6}$$

Therefore, the thermal efficiency is:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(h_2 - h_3) + (h_4 - h_5) - (h_1 - h_6)}{(h_2 - h_1) + (h_4 - h_3)} \tag{5.7}$$

5.3 c

If the HPT and LPT do not expand isentropically, our thermal efficiency will become:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(h_2 - h_{3'}) + (h_4 - h_{5'}) - (h_{1'} - h_6)}{(h_2 - h_{1'}) + (h_4 - h_{3'})} \tag{5.8}$$

As the enthalpies at the actual points is more than those at the ideal points, we see a net decrease in the thermal efficiency.

5.4 d

References

[1] Pawlowicz, R. (2013) Key Physical Variables in the Ocean: Temperature, Salinity, and Density. Nature Education Knowledge 4(4):13 https://www.nature.com/scitable/knowledge/library/key-physical-variables-in-the-ocean-temperature-102805293/ Accessed: 19/05/2021 00:00