

Template 4EB00

Special Topic: The Jet Engine

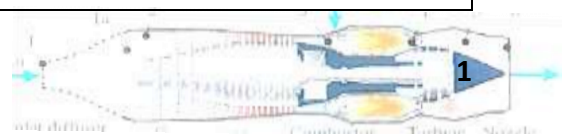
Groep 138

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2	Siebrand Keja	0886654

Assignment 1 The adiabatic flame temperature

```
clear all;close all;clc;
%%
warning off
abspath_to_generalfolder='C:\Users\s137280\Documents\tue leerjaar
2\Thermodynamics\Jet_Engine\Matlab\General'; % absolute reference to General
folder
addpath(abspath_to_generalfolder);
%% Load Nasadatabase
TdataBase=fullfile('General','NasaThermalDatabase');
load(TdataBase);
%% Some easy units
kJ=1e3;kmol=1e3;dm=0.1;bara=1e5;
%% Used by Nasa pols
global Runiv pref
Runiv=8.314472;
pref=1.01235e5; % Reference pressure, 1 atm!
Tref=298.15;    % Reference Temperature
%% Nasa is ready
TA=300; % Initial temperature
cFuel='Gasoline'; % Proper indices to database
iSp = myfind({Sp.Name},{cFuel,'O2','CO2','H2O','N2'});

%% Determine compositions Yi of initial and final mixture and do your stuff
SpS=Sp(iSp);
%% Subselection of the database in the order according to
{'Gasoline','O2','CO2','H2O','N2'}
NSp = length(SpS);
Mi = [SpS.Mass];
```



```

%% determine Aircomp and Fuelcomp
Xair = [0 0.21 0 0 0.79] ; %% mole fraction
Mair = Xair*Mi';
Yair = Xair.*Mi/Mair;
Yfuel = [1 0 0 0 0];

x = Sp(iSp(1)).Elcomp(3); %% line 33
y = Sp(iSp(1)).Elcomp(2); %% line 34
a = (x+(y/4)); %% line 35

MO2 = Sp(iSp(2)).Mass;
MN2= Sp(iSp(5)).Mass;
MF= Sp(iSp(1)).Mass;
MCO2= Sp(iSp(3)).Mass;
MH2O= Sp(iSp(4)).Mass;

MA=a*(MO2+(Xair(5)/Xair(2))*MN2); %% line 43
phi = [0.125:0.025:1];
%%AFstoi = (11.035*Mair/0.21)/Mi(1);
AF = (MA/MF)./phi; %% line 46

%% determine compositions mix AFstoi at beginning
YF = 1./(1+AF); %% line 49
YA = 1-YF; %% line 50
YO_before = 1/(1+(Xair(5)*MN2)/(Xair(2)*MO2)).*YA; %% line 51
YN2 = 1/(1+(Xair(2)*MO2)/(Xair(5)*MN2)).*YA; %% line 52

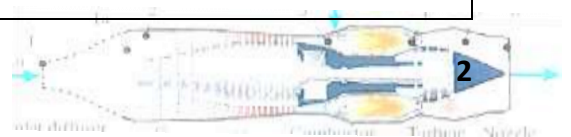
%% determine compositions mix AFstoi at end
YCO2 = (YF./MF).*x.*MCO2; %% line 55
YH2O = (YF./MF).*y/2.*MH2O; %% line 56
YO2after = 1-YCO2-YH2O-YN2; %% line 57

h1 = YF.*HNasa(TA,Sp(55))+YO_before.*HNasa(TA,Sp(4))+YN2.*HNasa(TA,Sp(48));
%% line 59

%% h2 for every temperature and mixture
i=1;
for T=200:1:3000
    for j = 1:length(AF)
        h2(i,j) =
YCO2(j)*HNasa(T,Sp(16))+YH2O(j)*HNasa(T,Sp(6))+YN2(j)*HNasa(T,Sp(48))+YO2aft
er(j)*HNasa(T,Sp(4)); %% line 65
    end
    i=i+1;
end

T_i = [200:1:3000];
for i=1:length(AF)
% Compute properties for all species for TR temperature range
T_ad(i) = interp1(h2(:,i),T_i,h1(i)); %%line 72
end

```



```

figure(1);
plot(phi,T_ad);
grid on;
xlabel('Equivalence ratio [-]');
ylabel('Temperature [K]');
title('Adiabatic temperature v.s. Equivalence ratio');

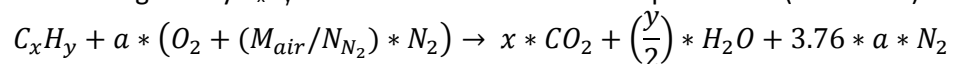
figure(2);
plot(AF,T_ad);
grid on;
xlabel('Air Fuel ratio [-]');
ylabel('Temperature [K]');
title('Adiabatic flame temperature v.s. Air Fuel ratio');

```

Code snippet

Explanation code snippet (formulas solved and connection with code snippet)

For a hydrocarbon fuel given by C_xH_y a stoichiometric reaction is expressed as (line 33-35):



Where: $a = x + y/4$

This relation is used to determine the mass of each component, the total fuel and total air used (line 46)

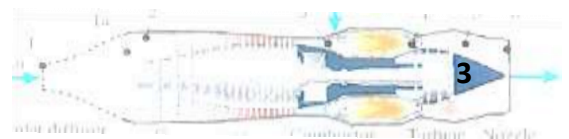
$$AF = (M_{air}/M_{fuel})/\phi$$

This relation together with the previous two are used to compute the mass fractions before and after the reaction.

First is solved the mass fraction of the fuel using (line 49):

$$Y_{fuel} = 1/(1 + AF)$$

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Then is solved the mass fraction of the air using (line 50):

$$Y_{air} = 1 - Y_{fuel}$$

Solving the mass fraction of Oxygen before combustion (line 51):

$$Y_{O_2} = \frac{1}{(1 + X_{N_2, in air} * \frac{M_{N_2}}{X_{O_2, in air} * M_{O_2}})} * Y_A$$

Solving the mass fraction of Nitrogen before/after combustion (this one stays the same) (line 52) :

$$Y_{N_2} = \frac{1}{(1 + X_{O_2, in air} * \frac{M_{O_2}}{X_{N_2, in air} * M_{N_2}})} * Y_A$$

Solving the mass fraction of CO₂ (line 55):

$$Y_{CO_2} = \frac{Y_f}{M_f} * x * M_{CO_2}$$

Solving the mass fraction of H₂O (line 56)

$$Y_{H_2O} = (Y_{fuel}/M_{fuel}) * y/2 * M_{H_2O}$$

Mixture properties before combustion determined using f.i. (line 59)

$$h(T) = \sum Y_i h_i(T)$$

Y_i at the beginning consists of Ymix1.

Mixture properties at temperature range of 200-3000K after combustion determined using f.i. (line 65)

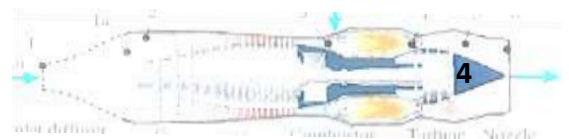
$$h(T) = \sum Y_i h_i(T)$$

Y_i at the end consists of Ymix2

Knowing the mass fractions before and after and due to definition of adiabatic flame temperature (line 72) :

$$h_{before combustion} = h_{after combustion}$$

The adiabatic flame temperatures can be determined, using the NASA tables and interpolation



Answer

Provide the following

1. Figure 1 Tb vs AF and Tb vs equivalence ratio. AF range AF_{stoi} to 8*AF_{stoi} .

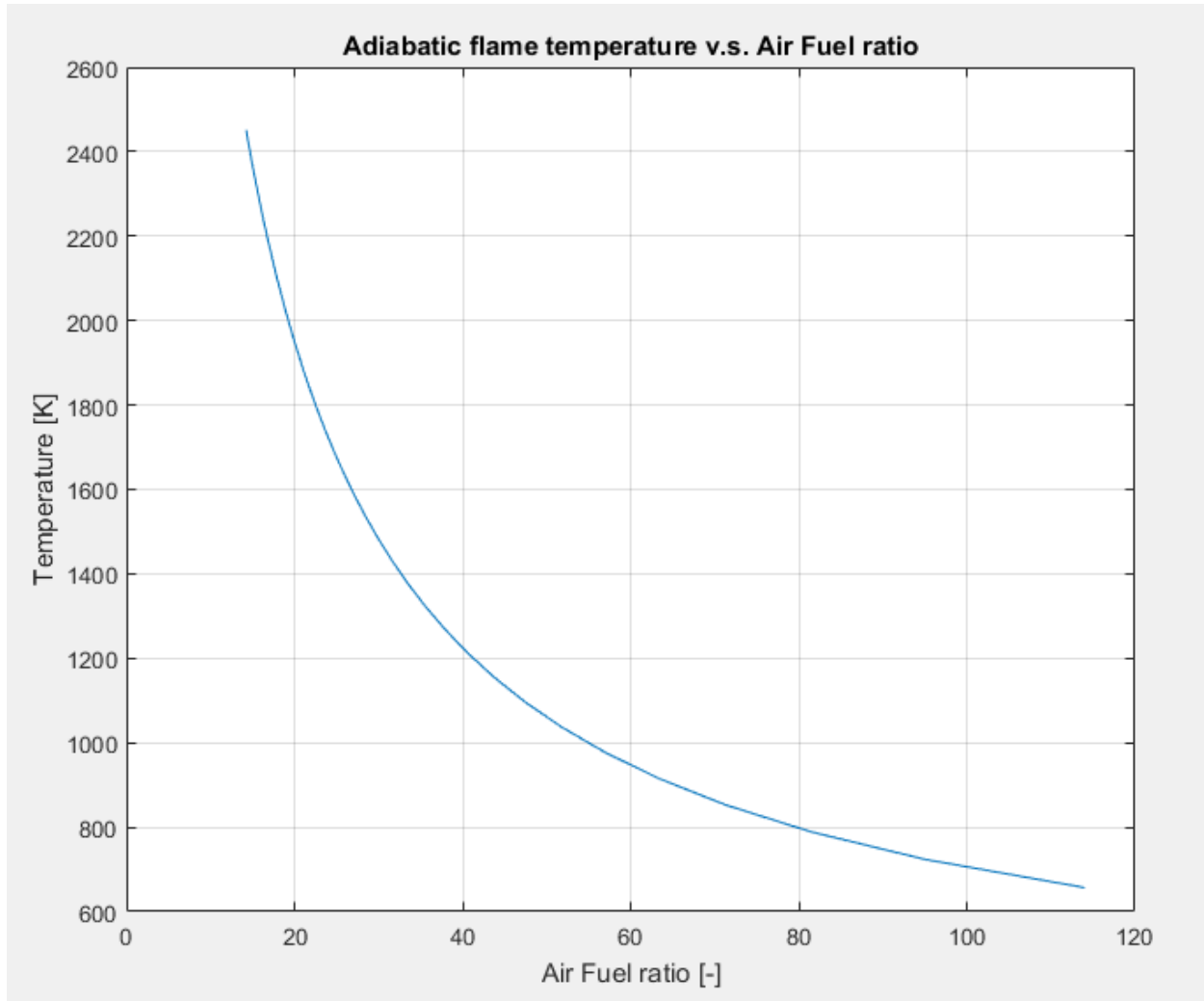
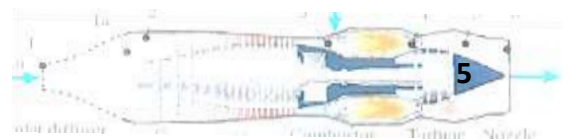


Figure 1. Adiabatic flame temperature versus. Air Fuel ratio



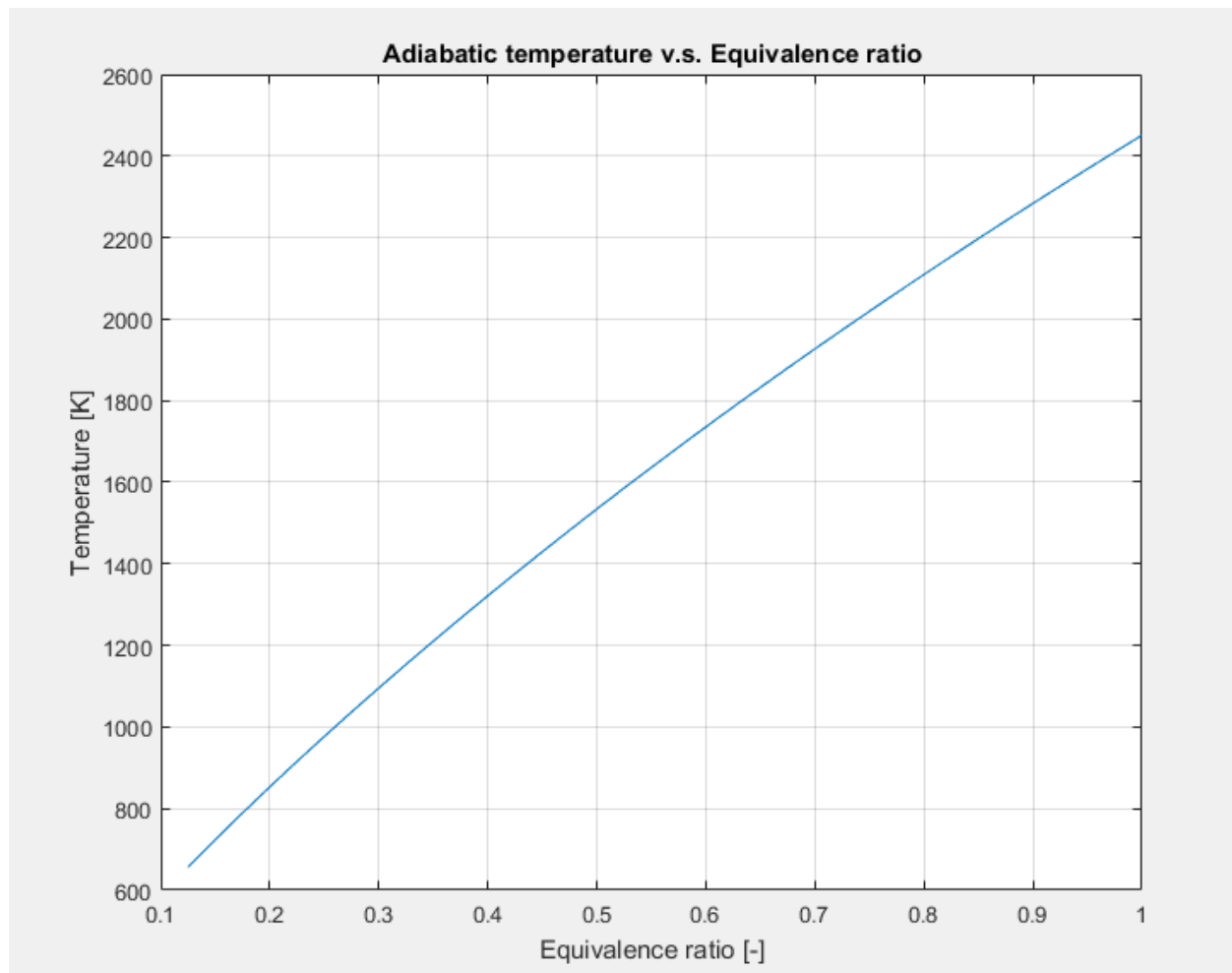
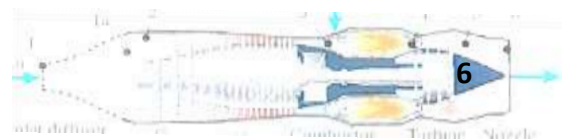


Figure 2. Adiabatic flame temperature versus Equivalence ratio

2. Tabel 1.1. **Include the value for AF_{stoi} (stoichiometric Air Fuel ratio) in the table header!**

	AF=AF _{stoi} AF_{stoi} =14.2483		AF=8*AF _{stoi}	
Mass fractions	Initial	Final	Initial	Final
Fuel	0,065581192716704	0	0.008696696343635	0
O ₂	0,217642503251585	0	0,230891898587318	0.202029486095615
N ₂	0,716776304031711	0,716776304031711	0,760411405069047	0.760411405069047
CO ₂	0	0.210499356595360	0	0.027914237436155
H ₂ O	0	0.072731316003760	0	0.009644871399183
Temp	298.15	2451.04	298.15	656.85

Table 1.1: Mixture composition and Temperature before and after combustion



Assignment 2 Cycle Analysis of the Jet Engine based on Nasa tables

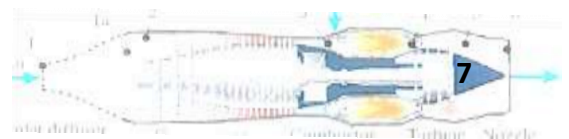
Applying conservation equations and the Nasa tables fill out table 2.1. The code and approach should be explained in detail in the following pages. As an example a worked-out part is given for the diffuser (page 5)

State	1	2	3	4	5	6
P (kPa)	55.00	71.84	502.88	502.88	236.02	55.00
T (K)	250.00	269.88	468.32	1002.81	830.38	566.57
v (m/s)	200.00	0.00	0.00	0.00	0.00	761.91

Table 2.1: Thermodynamic state summary

Diffusor

```
clear all;close all;clc;
%%
warning off
abspath_to_generalfolder='C:\Users\s137280\Documents\tue leerjaar
2\Thermodynamics\Jet_Engine\Matlab\General'; % absolute reference to General
folder
addpath(abspath_to_generalfolder);
%% Load Nasadatabase
TdataBase=fullfile('General','NasaThermalDatabase');
load(TdataBase);
%% Some convenient units
kJ=1e3;kmol=1e3;dm=0.1;bara=1e5;kPa = 1000;kN=1000;kg=1;s=1;
%% Used by Nasa pols should not be changed
global Runiv Pref
Runiv=8.314472;
Pref=1.01235e5; % Reference pressure, 1 atm!
Tref=298.15;    % Reference Temperature
%% Given conditions. Take the ones from your specific case
v1=200;Tamb=250;P3overP2=7;Pamb=55*kPa;mfurate=0.68*kg/s;AF=71.25;
% These are the ones from group 138
cFuel='Gasoline';
%% Select all species
iSp = myfind({Sp.Name},{cFuel,'O2','CO2','H2O','N2'});
SpS=Sp(iSp);
% Subselection of the database in the order according to
{'Gasoline','O2','CO2','H2O','N2'}
NSp = length(SpS);
Mi = [SpS.Mass];
%% Air comp
Xair = [0 0.21 0 0 0.79];           %line 25           % Order is important
MAir = Xair*Mi';
Yair = Xair.*Mi/MAir;               %line 27
%% Fuel comp
Yfuel = [1 0 0 0 0];
% Only fuel
%% Range of enthalpies/thermal part of entropy of species
TR = [200:1:3000];
```



```

for i=1:NSp
% Compute properties for all species for TR temperature range
    hia(:,i) = HNasa(TR,SpS(i));
    sia(:,i) = SNasa(TR,SpS(i));
end
hair_a= Yair*hia';
% enthalpy of air for range of T
sair_a= Yair*sia';
% thermal part of entropy of air for range of T
%% [1-2] Diffusor
sPart = 'Diffusor';
T1 = Tamb;
P1 = Pamb;
Rg = Runiv/MAir;
for i=1:NSp
    hi(i) = HNasa(T1,SpS(i));
end
h1 = Yair*hi';
v2=0; %% line 47
h2 = h1+0.5*v1^2-0.5*v2^2; %% line 48
T2 = interp1(hair_a,TR,h2); %% line 49
% Not exactly correct but nearly. Why??? can also do a search
for i=1:NSp
    hi2(i) = HNasa(T2,SpS(i));
    si1(i) = SNasa(T1,SpS(i));
    si2(i) = SNasa(T2,SpS(i));
end
h2check = Yair*hi2'; %% line 55
% Why do I do compute this h2check value? Any ideas?
s1thermal = Yair*si1';
s2thermal = Yair*si2';
lnPr = (s2thermal-s1thermal)/Rg;
Pr = exp(lnPr);
P2 = P1*Pr; %% line 60
S1 = s1thermal - Rg*log(P1/Pref);
S2 = s2thermal - Rg*log(P2/Pref);

```

Code snippet diffusor [1-2]

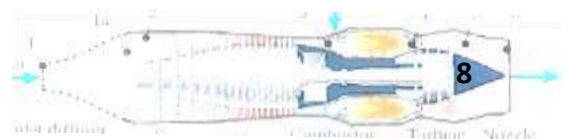
Procedure

Determine P_2T_2 & v_2

Because of energy conservation, solved is first (line 48)

$$h_2(T_2) = h_1(T_1) + \frac{1}{2}v_1^2$$

to determine T_2



Applying isentropic compression to solve for the pressure (line 60)

$$\int_{T_{ref}}^{T_2} \frac{C_p(T)}{T} dT - R_g \ln\left(\frac{P_2}{P_{ref}}\right) = \int_{T_{ref}}^{T_1} \frac{C_p(T)}{T} dT - R_g \ln\left(\frac{P_1}{P_{ref}}\right)$$

Mixture properties determined using f.i. (line 55)

$$h(T) = \sum Y_i h_i(T)$$

The composition Y_i is taken equal to that of normal air.

Because of isentropic process:

$S_1 = S_2$ (fig 8.19)

Also v_2 is equal to zero according to energy conservation (line 47).

Compressor

```
%% determining fractions of the mix at the beginning.

x = Sp(iSp(1)).Elcomp(3);           %% line 72
y = Sp(iSp(1)).Elcomp(2);           %% line 73
a = (x+(y/4));                       %% line 74

MO2 = Sp(iSp(2)).Mass;               %% line 76
MN2 = Sp(iSp(5)).Mass;
MF = Sp(iSp(1)).Mass;
MCO2 = Sp(iSp(3)).Mass;
MH2O = Sp(iSp(4)).Mass;              %% line 80

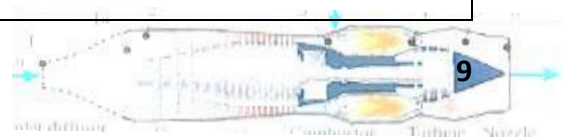
YF = 1./(1+AF);                      %% line 82
YA = 1-YF;                           %% line 83
YO_before = 1/(1+Xair(5)*MN2/(Xair(2)*MO2)).*YA; %% line 84
YN2 = 1/(1+(Xair(2)*MO2)/(Xair(5)*MN2)).*YA;    %% line 85

Ymix1 = [YF YO_before 0 0 YN2];      %% line 87
Nmix1 = Ymix1./Mi;
Xmix1 = Nmix1./sum(Nmix1);
Mmix1 = Xmix1.*Mi';

Xair = [0 0.21 0 0 0.79];
% Order is important
MAir = Xair.*Mi';
Yair = Xair.*Mi'/MAir;

%%determining fractions of the mix at the end
YCO2 = (YF./MF).*x.*MCO2;             %% line 97
YH2O = (YF./MF).* (y/2) .*MH2O;       %% line 98
YO2after = 1-YCO2-YH2O-YN2;           %% line 99

Yafter = [0 YO2after YCO2 YH2O YN2]; %% line 100
Nafter = Yafter./Mi;
Xafter = Nafter./sum(Nafter);
Mafter = Xafter.*Mi';
```



```

%%[2-3 compressor]
sPart='Compressor';
P3 = P2*P3overP2;                                %% line 108
s_druk3 = Rg*log(P3/Pref);                        %%s3 can be found since S2=S3 and P3 is
known
s3thermal = S2+s_druk3;                          %% line 110

T3 = interp1(sair_a,TR,s3thermal);               %% line 112 because we now s3thermal we
can find T3.
v3=0;                                             %%conservation of energy line 113

for i=1:Nsp
    hl(i) = HNasa(T3,SpS(i));
end
h3 = Yair*hl';                                  %% line 118

mairflow=mfurate*AF;                            %% line 121
Wincomp = mairflow*(h3-h2);                      %% line 122

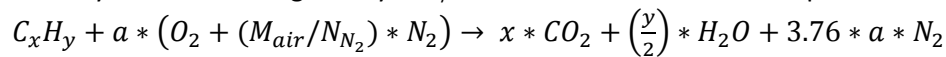
```

Code snippet Compressor [2-3]

Procedure

Line nr. (72 till 74):

For a hydrocarbon fuel given by C_xH_y , a stoichiometric reaction is expressed as:



Where: $a = x + y/4$ (line 74)

This relation is used to determine the mass of each component, the total fuel and total air used.

First is solved the mass fraction of the fuel using (line 82):

$$Y_{fuel} = 1/(1 + AF)$$

Then is solved the mass fraction of the air using (line 83):

$$Y_{air} = 1 - Y_{fuel}$$

Solving the mass fraction of Oxygen before combustion (line 84):

$$Y_{O_2} = \frac{1}{(1 + X_{N_2, in air} * \frac{M_{N_2}}{X_{O_2, in air} * M_{O_2}})} * Y_A$$

Solving the mass fraction of Nitrogen before/after combustion (this one stays the same) (line 85) :

$$Y_{N_2} = \frac{1}{(1 + X_{O_2, in air} * \frac{M_{O_2}}{X_{N_2, in air} * M_{N_2}})} * Y_A$$

The total mass fraction before combustion (line 87)

$$Y_{mix1} = Y_{fuel} + Y_{O_2} + Y_{N_2}$$

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Solving the mass fraction of CO₂ (line 97):

$$Y_{CO_2} = \frac{Y_f}{M_f} * x * M_{CO_2}$$

Solving the mas fraction of H₂O (line 98)

$$Y_{H_2O} = (Y_{fuel}/M_{fuel}) * y/2 * M_{H_2O}$$

Solving the mass fraction of Oxygen after combustion (line 99):

$$Y_{O_2} = \frac{1}{(1+X_{N_2, in air} * \frac{M_{N_2}}{X_{O_2, in air} * M_{O_2}})} * Y_A$$

The total mass fraction after combustion (line 100):

$$Y_{mix2} = Y_{CO_2} + Y_{H_2O} + Y_{O_2} + Y_{N_2}$$

Determine $P_3 T_3$ & v_3

Compressor ratio is given so P_3 can be calculated using: (line 108):

$$P_3 = P_2 * \frac{P_3}{P_2}$$

No v_3 according to energy conservation (line113)

Because of reversible (isentropic) compression and knowing P_3 , T_3 can be determined using (with SNasa and interpolation) (line 112):

$$\int_{T_{ref}}^{T_2} \frac{C_p(T)}{T} dT - R_g \ln \left(\frac{P_2}{P_{ref}} \right) = \int_{T_{ref}}^{T_3} \frac{C_p(T)}{T} dT - R_g \ln \left(\frac{P_3}{P_{ref}} \right)$$

Mixture properties determined using f.i. (line 118)

$$h(T) = \sum Y_i h_i(T)$$

The composition Y_i is taken equal to that of normal air.

The mass rate of air can be calculated because the mass rate of the fuel is known (line 121)

$$\dot{m}_{airflow} = \dot{m}_{fuel} * AF$$

With h_3 and the mass rate of air $\dot{W}_{in,comp}$ can be calculated. (line 122)

$$-\dot{W}_{in} = \dot{m}_{airflow} (h_3 - h_2)$$



Combustor

```
sPart='Combustor';
%% h3 = h4 line 132
P4=P3; %% line 133 the pressure is constant

%% T4 is adiabaticflame temperature
h_4= Ymix1*hl'; %% line 136
h4 = Yafter*hia'; %% line 137
T4 = interp1(h4,TR,h_4); %% line 138
for i=1:Nsp
    hl2(i) = HNasa(T4,SpS(i)); %% line 140
end
h4check = Yafter*hl2';

for i=1:Nsp
    si4(i) = SNasa(T4,SpS(i));
end
s4thermal = Yafter*si4';
s4thermal = sum(s4thermal);

%% Rg2= Runiv/Mafter

S4 = s4thermal - Rg*log(P4/Pref) ; %% line 152

v4 = 0; %% line energy conversation %% line 154
```

Code snippet Combustor [3-4]

Procedure

Determine $P_4 T_4$ & v_4 and complete table 2.2

Because of definition of adiabatic combustion $h_4 = h_3$

The mass fraction before changes from complete air to air with fuel, because fuel is added (=mix1), the temperature isn't changed yet.

Mixture properties determined using f.i. (line 136)

$$h(T) = \sum Y_i h_i(T)$$

The composition Y_i is taken equal to that of normal air with the fuel (mix1).

Mix1 becomes mix2 after combustion.

Because it is an isobaric process (line 133):

$$P_3 = P_4$$



Mixture properties determined at a range for $T=200-3000$ K using f.i. (line 137)

$$h(T) = \sum Y_i h_i(T)$$

The composition Y_i is taken equal to that of normal air with CO_2 and H_2O (mix2).

T_4 can be determined by interpolation (line 138).

Energy conservation (line 154):

$$\dot{m}_{out} h_{out} = \dot{m}_{air} h_{air} + \dot{m}_{fuel} h_{fuel}$$

So v_4 equals zero

Because T_4 and P_4 are known, determining the entropy at stage 4 using (line 152):

$$S_4 = \int_{T_{ref}}^{T_4} \frac{C_p(T)}{T} dT - R_g \ln \left(\frac{P_4}{P_{ref}} \right)$$

The composition Y_i is taken equal to that of normal air with CO_2 and H_2O (mix2).

AF=71.25		
Mass fractions	Initial	Final
Fuel	0,013840830449827	0
O ₂	0,229693739672700	0,183759083351967
N ₂	0,756465429877473	0,756465429877473
CO ₂	0	0,044425631552931
H ₂ O	0	0,015349855217629

Table 2.2: Mixture composition before and after the combustor



Turbine

```
sPart = 'Turbine';

h5 = h4check-(mairflow*(h3-h2)/(mairflow+mfurate)); %% line 163 conservation
of energy
v5 = 0; %% line 164

h_5 = Yafter*hia'; %% line 166
T5 = interp1(h_5,TR,h5); %% line 167
for i=1:Nsp
    hi5(i) = HNasa(T5,SpS(i));
end
h5check = Yafter*hi5';

for i=1:Nsp
    si5(i) = SNasa(T5,SpS(i));
end
s5thermal = Yafter*si5';

lnPr2 = (s5thermal-s4thermal)/Rg;
Pr2 = exp(lnPr2);
P5 = P4*Pr2; %% line 180
S4 = s4thermal - Rg*log(P4/Pref);
S5 = s5thermal - Rg*log(P5/Pref);
```

Code snippet Turbine [4-5]

Procedure

Determine $P_5 T_5$ & v_5

According to conservation of energy:

$$-\dot{W}_{out} = \dot{m}_{airflow+fuelrate}(h_5 - h_4)$$

The total mass in and out are the same. However the mass rate which causes : \dot{W}_{in} is only the mass rate of air

And since: $\dot{W}_{in} = \dot{W}_{out}$ we can write (line 163):

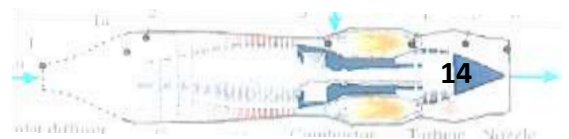
$$h_5 = h_4 - (\dot{m}_{air rate} * (h_3 - h_2)) / (\dot{m}_{air rate} + \dot{m}_{fuel rate})$$

Mixture properties determined at a range for T=200-3000 K using f.i. (line 166)

$$h(T) = \sum Y_i h_i(T)$$

The composition Y_i is taken equal to that of normal air with CO₂ and H₂O (mix2).

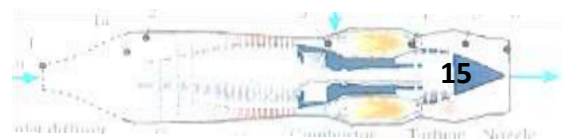
T₅ can be determined by interpolation. (line 167).



Because of isentropic process (fig 8. 19) the pressure at stage 5 can be determined using: (line 180)

$$\int_{T_{ref}}^{T_4} \frac{c_p(T)}{T} dT - R_g \ln \left(\frac{P_4}{P_{ref}} \right) = \int_{T_{ref}}^{T_5} \frac{c_p(T)}{T} dT - R_g \ln \left(\frac{P_5}{P_{ref}} \right)$$

No v_5 according to energy conservation so equals zero (line 164)



Nozzle

```
sPart = 'Nozzle';

P6 = Pamb;                                %%line 191
s_druk6 = Rg*log(P6/Pref);
s6thermal = S5+s_druk6;
s_6= Yafter*sia';

T6 = interp1(s_6,TR,s6thermal);           %%line 196
for i=1:NSp
    hi6(i) = HNasa(T6,SpS(i));
end
h6 = Yafter*hi6';
v6 = (2*(h5-h6))^0.5;                      %%line 201
```

Code snippet Nozzle [5-6]

Procedure

Determine P_6 , T_6 & v_6

P_6 is given (line 191)

$$P_6 = P_{amb} = P_1 = 55 \text{ kPa}$$

Because it's an isentropic process, using (line 196):

$$\int_{T_{ref}}^{T_5} \frac{C_p(T)}{T} dT - R_g \ln\left(\frac{P_5}{P_{ref}}\right) = \int_{T_{ref}}^{T_6} \frac{C_p(T)}{T} dT - R_g \ln\left(\frac{P_6}{P_{ref}}\right)$$

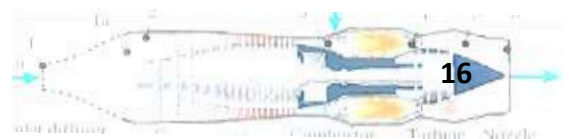
To find the temperature at stage 6

Mixture properties determined using f.i. (line 200)

$$h(T) = \sum Y_i h_i(T)$$

The composition Y_i is taken equal to that of normal air with CO_2 and H_2O (mix2).

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According to energy conservation:

$$h_5 = h_6 + \frac{1}{2} v_6^2$$

Now it is also possible to calculate v_6 (line 201)

$$v_6 = [2 * (h_5 - h_6)]^{1/2}$$

