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Power Cycle Components/Processes

by

Engineering Software

Power Cycle Components/Processes

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Compression

This section provides an isentropic compression analysis when the working fluid is air.

Analysis

In the presented compression analysis, only air is considered as the working fluid behaving as a perfect gas -- specific heat has a constant value. Ideal gas state equation is valid -- pv = RT.

Air enters a compressor at point 1 and it exits the compressor at point 2. Isentropic compression is considered with no entropy change.

Figure 1 presents a compression schematic layout.

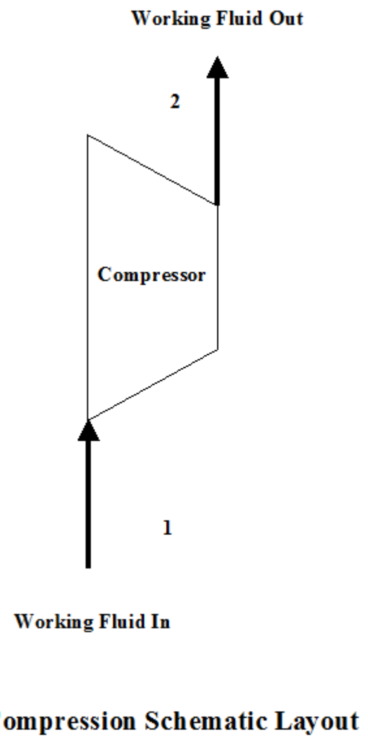

Figure 1 - Compression Schematic Layout

Power Cycle Components/Processes

Figure 2 presents a compression temperature vs entropy diagram.

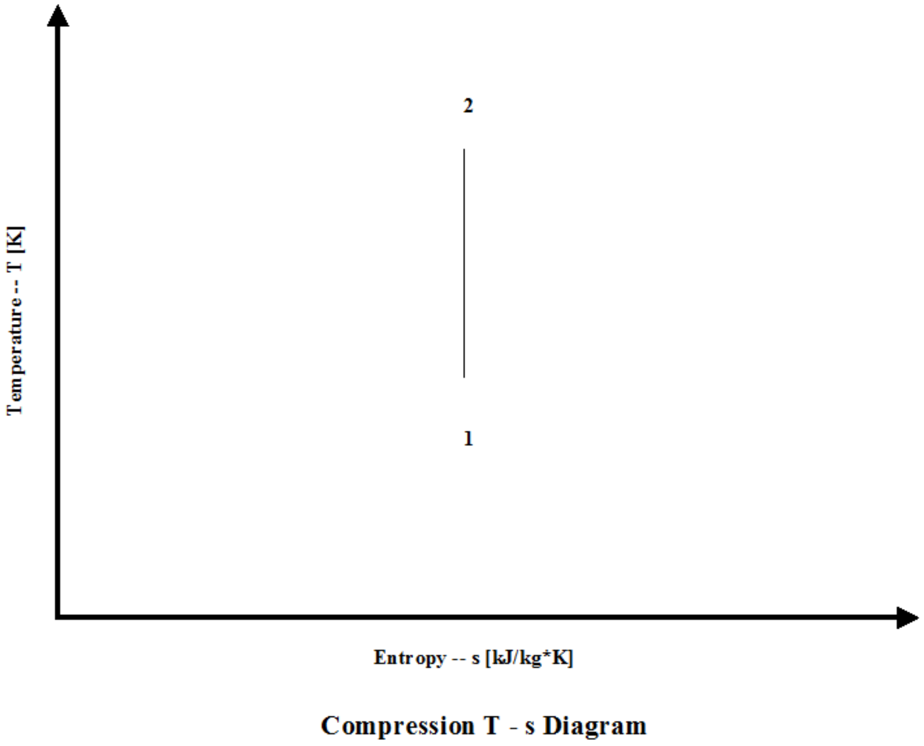

Figure 2 - Compression Temperature vs Entropy Diagram

Figure 3 presents compression specific power input requirements for a few typical compression ratio values. It should be noted that the air enters the compressor at standard ambient conditions of 298 [K] and 1 [atm] of absolute pressure.

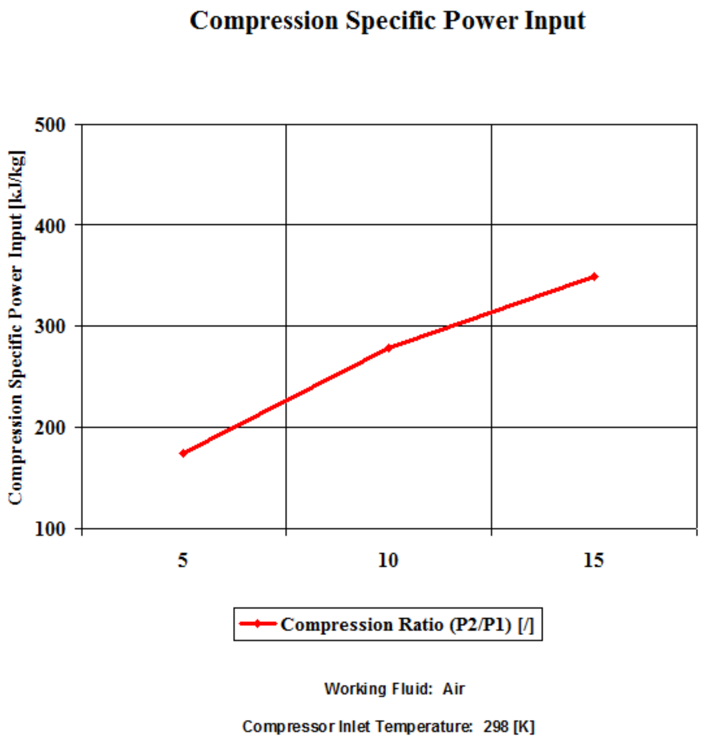

Figure 3 - Compression Specific Power Input

Figure 4 presents compression power input requirements for two typical compression ratio values and a few different working fluid mass flow rate values.

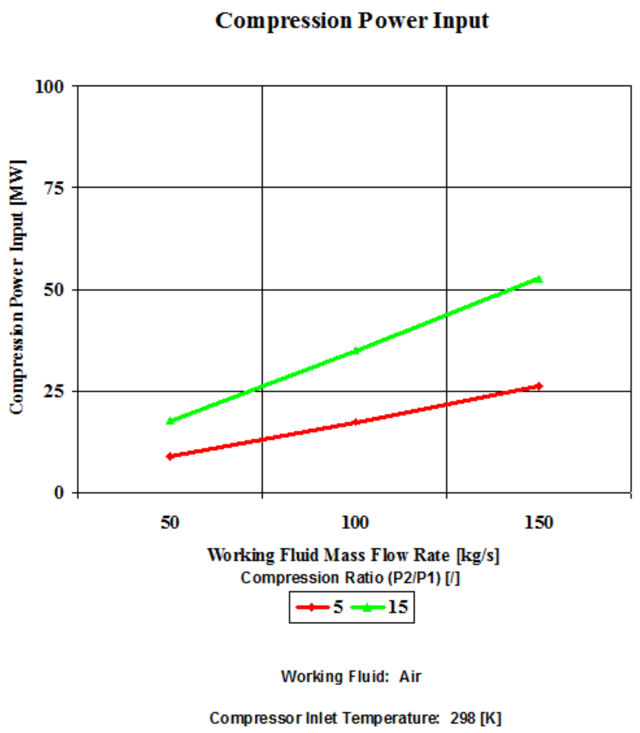

Figure 4 - Compression Power Input

One can notice that both compression specific power input and power input increase with an increase in the compression ratio values. As the working fluid mass flow rate increases for a fixed compression inlet temperature value, the compression power input requirements increase too.

Assumptions

Working fluid is air. There is no friction and heat transfer. Compression is isentropic -- there is no entropy change. Ideal gas state equation is valid -- pv = RT. Air behaves as a perfect gas -- specific heat has a constant value.

Power Cycle Components/Processes

Governing Equations

$$T_2/T_1 = (p_2/p_1)^{(\varkappa-1)/\varkappa}$$

$$\varkappa = c_p/c_v$$

$$c_p - c_v = R$$

$$pv = RT$$

$$w = c_p(T_2 - T_1)$$

$$W = c_p(T_2 - T_1)m$$

Input Data

$T_1 = 298$ [K]

$p_1 = 1$ [atm]

$p_2 = 5$, 10 and 15 [atm]

$R = 0.2867$ [kJ/kg*K]

$c_p = 1.004$ [kJ/kg*K]

$\varkappa = 1.4$ [/]

$m = 50$, 100 and 150 [kg/s]

Results

Specific Power Input vs Compression Ratio
Compression Inlet Temperature = 298 [K]

Compression Ratio [/]	Specific Power Input [kW/kg/s]
5	174
10	278
15	349

Power Input vs Compression Ratio for a few Mass Flow Rates
Compression Inlet Temperature = 298 [K]

Power Input [MW]	**Mass Flow Rate [kg/s]**		
Compression Ratio [/]	50	100	150
5	8.68	17.37	26.05
15	17.47	34.94	52.41

Conclusions

Both compression specific power input and power input increase with an increase the compression ratio values. As the working fluid mass flow rate increases for a fixed compression inlet temperature value, the compression power input requirements increase too.

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Combustion

This section provides a combustion analysis for a few typical fuel cases (carbon, hydrogen, sulfur, coal, oil and gas) when the fuel reacts with air at stoichiometric conditions.

Analysis

In the presented combustion analysis, both fuel and air are at standard inlet combustion conditions of 298 [K] and 1 [atm] of absolute pressure. Furthermore, combustion at constant pressure is complete and with no heat loss.

During combustion, a large amount of reactants' chemical energy gets released in the form of thermal energy.

Fuel higher heating value (HHV) or heat of combustion is the difference between the reactants enthalpy value and the combustion products enthalpy value per unit mass amount of fuel at the standard reference temperature, which is 298 [K].

When the reactants specific enthalpy value is equal to the combustion products specific enthalpy value, one can calculate the combustion products flame temperature or adiabatic temperature.

Figure 1 presents how the reactants and combustion products specific enthalpy values change with an increase in the temperature.

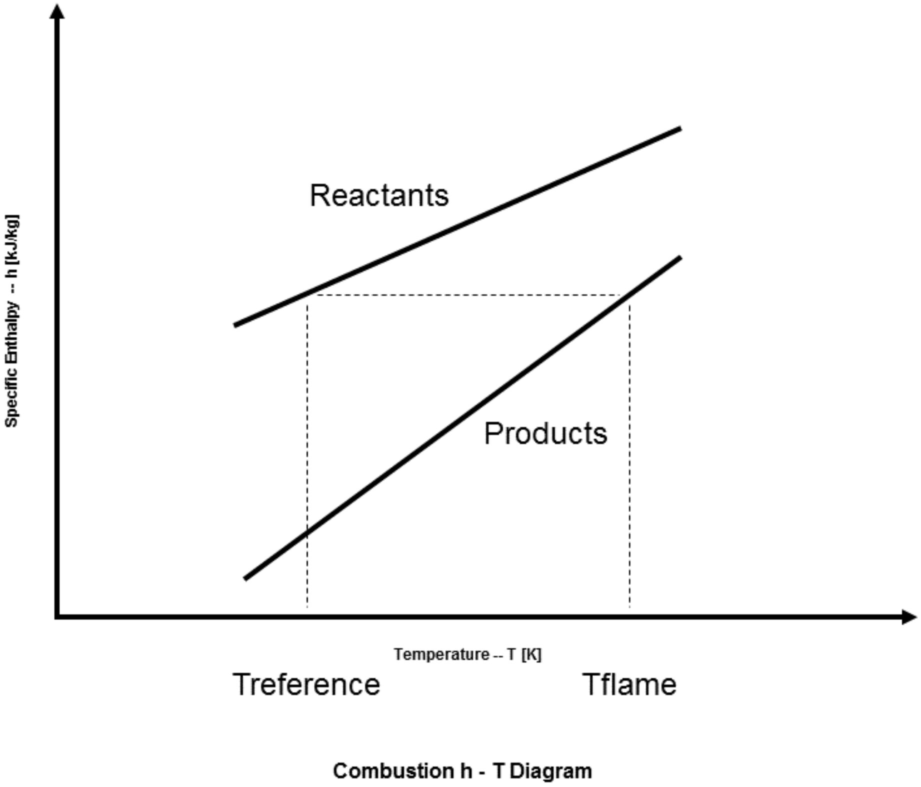


Figure 1 - Reactants and Combustion Products Specific Enthalpy vs Temperature

Physical properties for both reactants and combustion products are very important and need to be known in order to carry out successful combustion calculations.

Figure 2 depicts how the reactants and combustion products species specific enthalpy values change with the temperature. The physical properties provided in Figure 2 come from the JANAF Thermochemical Data - Tables, 1970.

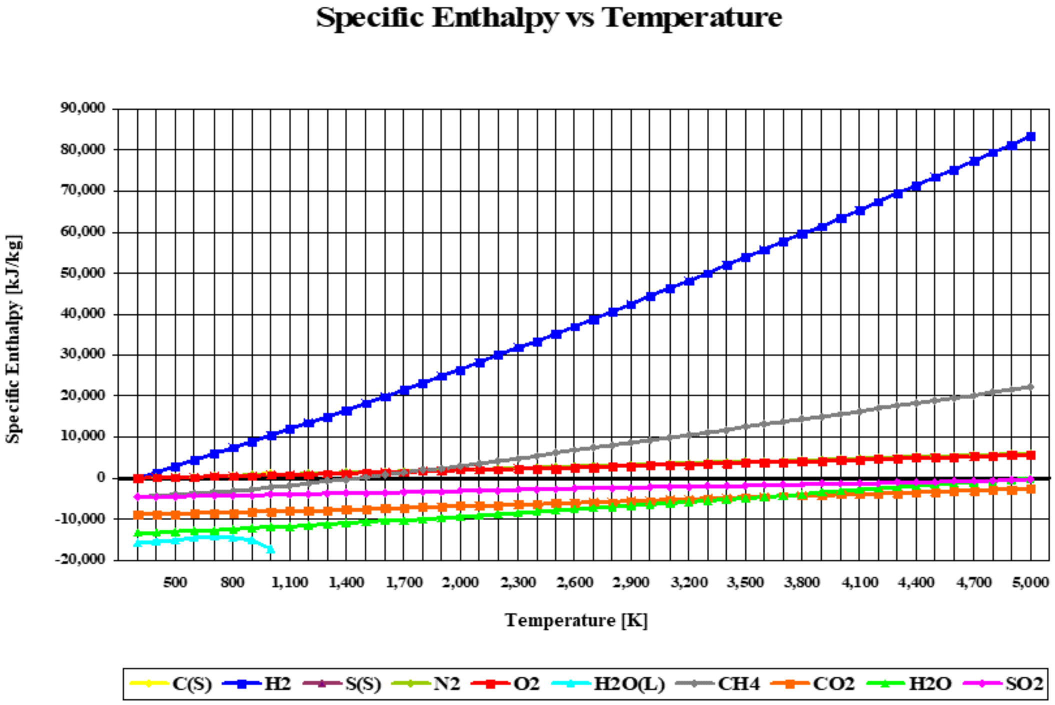


Figure 2 - Reactants and Combustion Products Species Specific Enthalpy vs Temperature

It is interesting to note that the specific enthalpy value for basic combustion elements such as carbon (C), hydrogen (H_2), sulfur (S), oxygen (O_2) and nitrogen (N_2) is equal to zero at the standard combustion conditions of 298 [K] and 1 [atm].

Also, it should be mentioned that for ideal gas species, the specific enthalpy values are only dependent on the temperature.

In addition to knowing the reactants and combustion products physical properties, for any kind of combustion analysis and calculations, it is important to know both oxidant and fuel compositions.

Oxidant composition is usually given on the mole/volume basis. For solid and liquid type fuels, the fuel composition is given on the weight basis for a unit mass amount. For the gas type fuels, the fuel composition is provided on the mole/volume basis for a unit volume amount. In this analysis, methane (CH_4) is considered as the gas fuel. In order to keep the combustion analysis simple and straightforward, the CH_4 composition is provided on the weight basis.

Table 1 provides the standard air composition.

Table 1 - Oxidant Composition

Oxidant	N [kg/kg]	O [kg/kg]	N [kmol/kmol]	O [kmol/kmol]
Air	0.767	0.233	0.790	0.210

Table 2 provides the fuel composition.

Table 2 - Fuel Composition

Fuel	C [kg/kg]	H [kg/kg]	S [kg/kg]	N [kg/kg]	O [kg/kg]	H_2O [kg/kg]	CH_4 [kg/kg]
Carbon	1.000	0.000	0.000	0.000	0.000	0.000	-
Hydrogen	0.000	1.000	0.000	0.000	0.000	0.000	-
Sulfur	0.000	0.000	1.000	0.000	0.000	0.000	-
Coal	0.780	0.050	0.030	0.040	0.080	0.020	-
Oil	0.860	0.140	0.000	0.000	0.000	0.000	-
Gas	-	-	-	-	-	-	1.000

Again, in this combustion analysis, only the stoichiometric combustion is analyzed. Results of such analysis are provided, including combustion products composition on weight and mole/volume basis, flame temperature, stoichiometric oxidant to fuel ratio and fuel higher heating value (HHV).

Table 3 provides the combustion products composition on the weight basis.

Table 3 - Combustion Products Composition on the Weight Basis

Fuel	CO_2 [kg/kg]	H_2O [kg/kg]	SO_2 [kg/kg]	N_2 [kg/kg]	O_2 [kg/kg]
Carbon	0.295	0.000	0.000	0.705	0.000
Hydrogen	0.000	0.255	0.000	0.745	0.000
Sulfur	0.000	0.000	0.378	0.622	0.000
Coal	0.249	0.041	0.005	0.705	0.000
Oil	0.202	0.080	0.000	0.718	0.000
Gas	0.151	0.124	0.000	0.725	0.000

Table 4 provides the combustion products composition on the mole basis.

Table 4 - Combustion Products Composition on the Mole Basis

Fuel	CO_2 [kmol/kmol]	H_2O [kmol/kmol]	SO_2 [kmol/kmol]	N_2 [kmol/kmol]	O_2 [kmol/kmol]
Carbon	0.210	0.000	0.000	0.790	0.000
Hydrogen	0.000	0.347	0.000	0.653	0.000
Sulfur	0.000	0.000	0.210	0.790	0.000
Coal	0.170	0.068	0.002	0.759	0.000
Oil	0.132	0.129	0.000	0.739	0.000
Gas	0.095	0.190	0.000	0.715	0.000

When considering coal, oil and gas as the fuel, coal has the largest amount of CO_2 in the combustion products on both weight and mole basis.

Table 5 provides the combustion products flame temperature, stoichiometric oxidant to fuel ratio and the fuel higher heating value.

Table 5 - Combustion Products Flame Temperature, Stoichiometric Oxidant to Fuel Ratio and Fuel Higher Heating Value

Fuel	Flame Temperature [K]	Stoichiometric Oxidant to Fuel Ratio [/]	HHV [Btu/lbm]
Carbon	2,460	11.444	14,094
Hydrogen	2,525	34.333	60,997
Sulfur	1,972	4.292	3,982
Coal	2,484	10.487	14,162
Oil	2,484	14.649	20,660
Gas	2,327	17.167	21,563

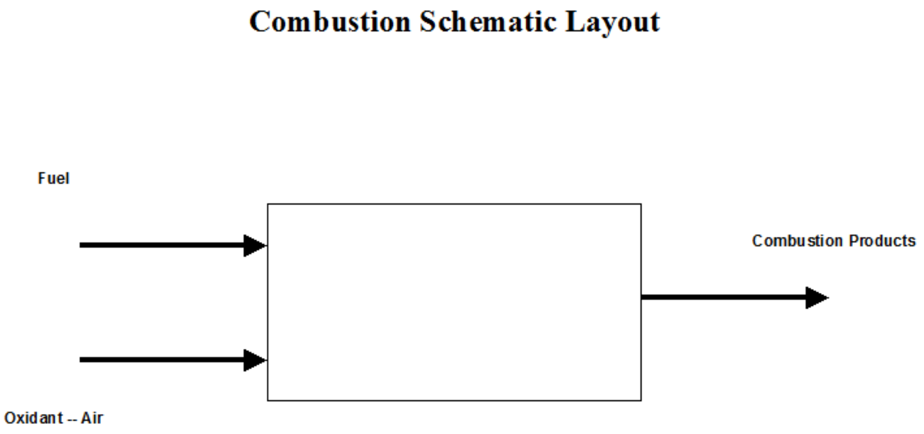
Stoichiometric oxidant to fuel ratio is the mass of air required for complete combustion of a unit mass of fuel. Thus, 1 [kg] of carbon fuel requires 11.444 [kg] of air for complete, ideal combustion.

Today, global warming is becoming more evident and it is being said that it is primarily caused by CO_2 emissions. A detailed combustion analysis, as it is provided here, can be very useful in determining different fuel and technology scenarios that would result in the reduction of current CO_2 emissions.

Assumptions

Both fuel and air are at standard inlet combustion conditions of 298 [K] and 1 [atm] of absolute pressure.

Furthermore, combustion is complete and with no heat loss.



Combustion Schematic Layout

Species Molecular Weight

Species	C	H_2	S	O_2	N_2	CO_2	H_2O	SO_2	CH_4
Molecular Weight [kg/kmol]	12	2	32	32	28	44	18	64	16

Stoichiometric Oxidant and Combustion Products Mole Flow Rates for 1 [kmol] of Fuel Species

	Fuel Composition				**Oxidant Composition**		**Combustion Products Composition**				
Fuel	**C [kmol]**	**H_2 [kmol]**	**S [kmol]**	**CH_4 [kmol]**	**O_2 [kmol]**	**N_2 [kmol]**	**CO_2 [kmol]**	**H_2O [kmol]**	**SO_2 [kmol]**	**O_2 [kmol]**	**N_2 [kmol]**
Carbon	1	0	0	0	1	3.762	1	0	0	0	3.762
Hydrogen	0	1	0	0	0.5	1.881	0	1	0	0	1.881
Sulfur	0	0	1	0	1	3.762	0	0	1	0	3.762
Coal	1	1	1	0	2.5	9.404	1	1	1	0	9.404
Oil	1	1	0	0	1.5	5.642	1	1	0	0	5.642
Gas	0	0	0	1	2	7.524	1	2	0	0	7.524

Stoichiometric Oxidant to Fuel Ratio, Oxidant and Combustion Products Mass Flow Rates for 1 [kmol] of Fuel Species

	Fuel Composition				**Oxidant Composition**		**Combustion Products Composition**				**Stoichiometric Oxidant to Fuel Ratio [/]**
Fuel	**C [kg]**	**H_2 [kg]**	**S [kg]**	**CH_4 [kg]**	**O_2 [kg]**	**N_2 [kg]**	**CO_2 [kg]**	**H_2O [kg]**	**SO_2 [kg]**	**O_2 [kg]**	**N_2 [kg]**	
Carbon	12	0	0	0	32	105.336	44	0	0	0	105.336	11.444
Hydrogen	0	2	0	0	16	52.668	0	18	0	0	52.668	34.333
Sulfur	0	0	32	0	32	105.336	0	0	64	0	105.336	4.292
Coal	12	2	32	0	80	263.312	44	18	64	0	263.312	7.463
Oil	12	2	0	0	48	157.976	44	18	0	0	157.976	14.712
Gas	0	0	0	16	64	210.672	44	36	0	0	210.672	17.167

Governing Equations

Fuel higher heating value (HHV) or heat of combustion is the difference between the reactants enthalpy value and the combustion products enthalpy value per unit mass amount of fuel at the standard reference temperature, which is 298 [K].

When the reactants specific enthalpy value is equal to the combustion products specific enthalpy value, one can calculate the combustion products flame temperature or adiabatic temperature.

Input Data

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Oxidant	N [kg/kg]	O [kg/kg]	N [kmol/kmol]	O [kmol/kmol]
Air	0.767	0.233	0.790	0.210

Table 2 - Fuel Composition

Fuel	C [kg/kg]	H [kg/kg]	S [kg/kg]	N [kg/kg]	O [kg/kg]	H_2O [kg/kg]	CH_4 [kg/kg]
Carbon	1.000	0.000	0.000	0.000	0.000	0.000	-
Hydrogen	0.000	1.000	0.000	0.000	0.000	0.000	-
Sulfur	0.000	0.000	1.000	0.000	0.000	0.000	-
Coal	0.780	0.050	0.030	0.040	0.080	0.020	-
Oil	0.860	0.140	0.000	0.000	0.000	0.000	-
Gas	-	-	-	-	-	-	1.000

Results

Table 3 - Combustion Products Composition on the Weight Basis

Fuel	CO_2 [kg/kg]	H_2O [kg/kg]	SO_2 [kg/kg]	N_2 [kg/kg]	O_2 [kg/kg]
Carbon	0.295	0.000	0.000	0.705	0.000
Hydrogen	0.000	0.255	0.000	0.745	0.000
Sulfur	0.000	0.000	0.378	0.622	0.000
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Oil	0.202	0.080	0.000	0.718	0.000
Gas	0.151	0.124	0.000	0.725	0.000

Table 4 - Combustion Products Composition on the Mole Basis

Fuel	CO_2 [kmol/kmol]	H_2O [kmol/kmol]	SO_2 [kmol/kmol]	N_2 [kmol/kmol]	O_2 [kmol/kmol]
Carbon	0.210	0.000	0.000	0.790	0.000
Hydrogen	0.000	0.347	0.000	0.653	0.000
Sulfur	0.000	0.000	0.210	0.790	0.000
Coal	0.170	0.068	0.002	0.759	0.000
Oil	0.132	0.129	0.000	0.739	0.000
Gas	0.095	0.190	0.000	0.715	0.000

Table 5 - Combustion Products Flame Temperature, Stoichiometric Oxidant to Fuel Ratio and Fuel Higher Heating Value

Fuel	Flame Temperature [K]	Stoichiometric Oxidant to Fuel Ratio [/]	HHV [Btu/lbm]
Carbon	2,460	11.444	14,094
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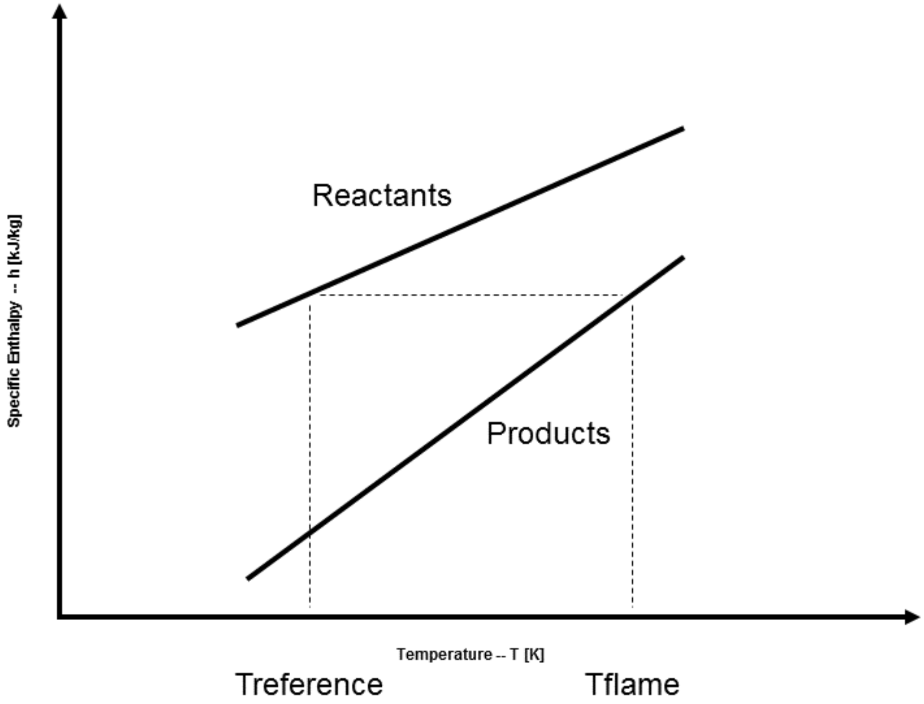
Figures



Combustion h - T Diagram

Figure 1 - Reactants and Combustion Products Specific Enthalpy vs Temperature

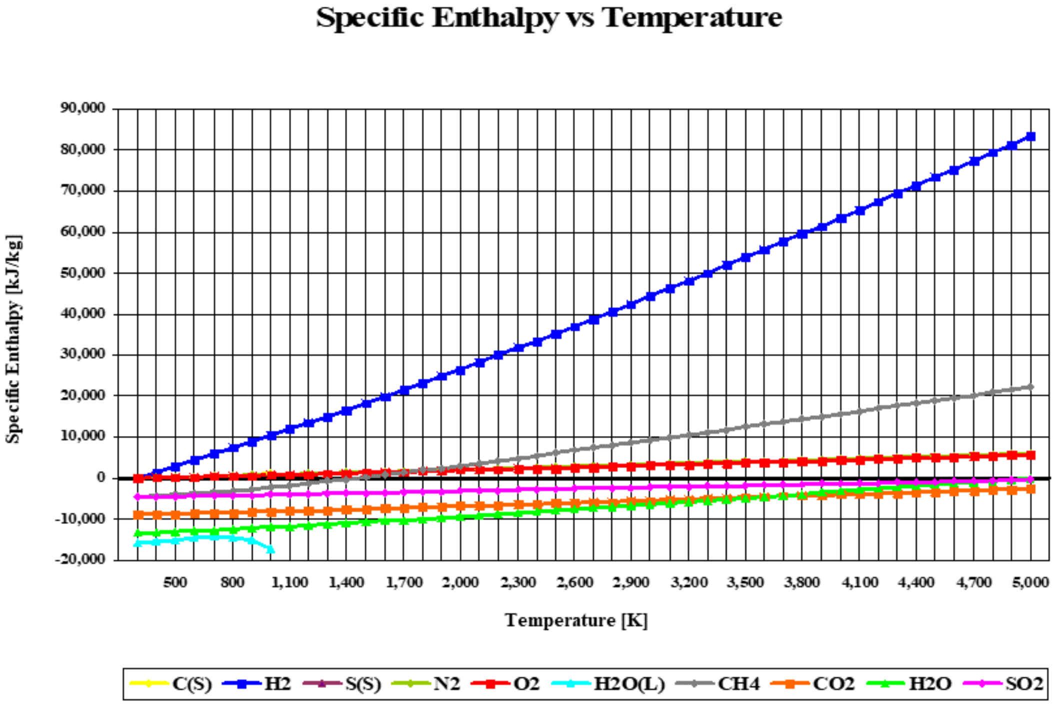
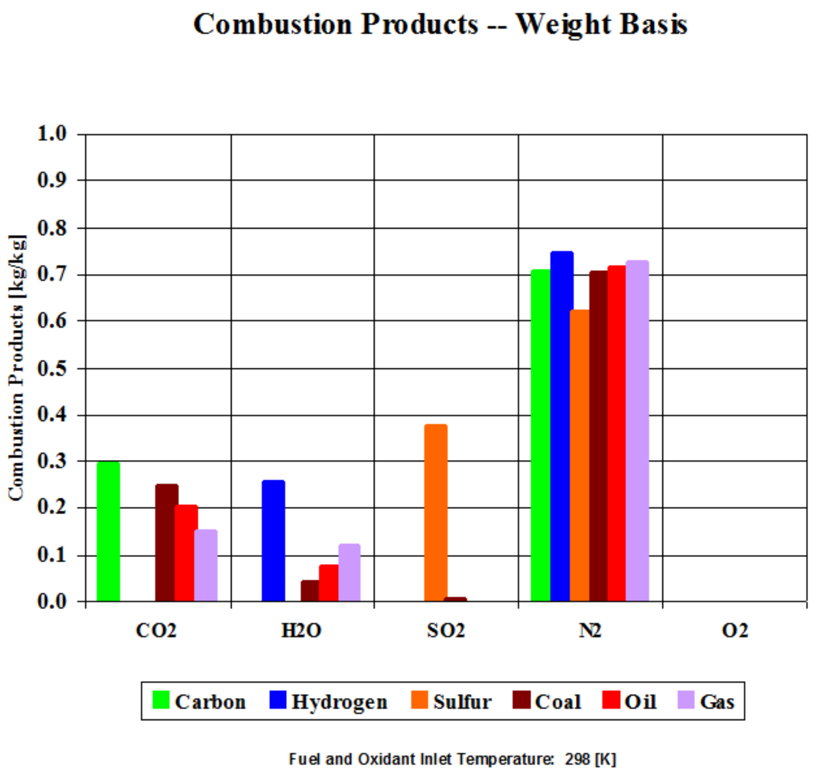
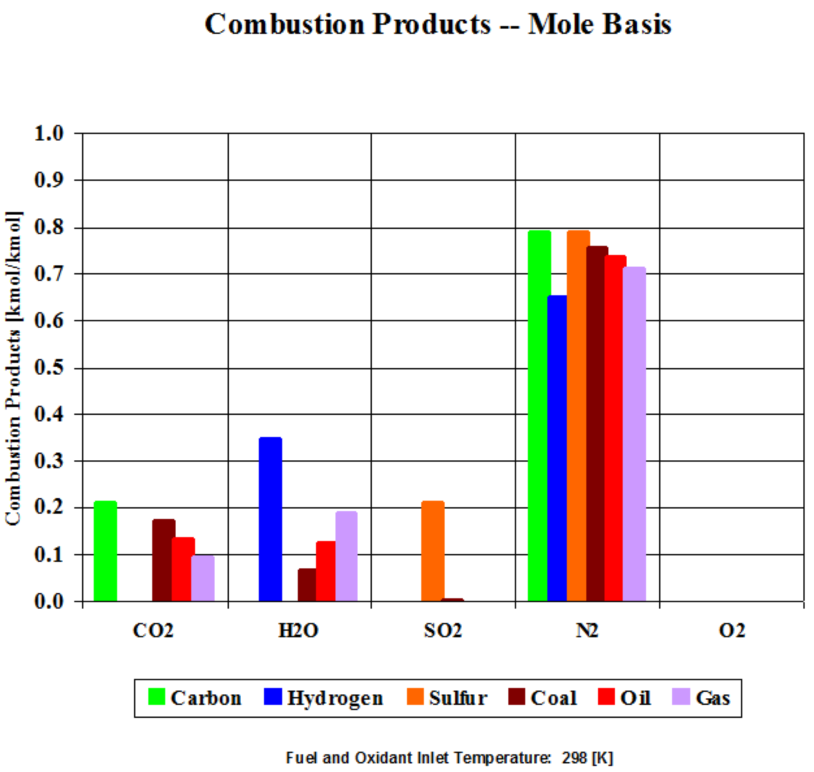


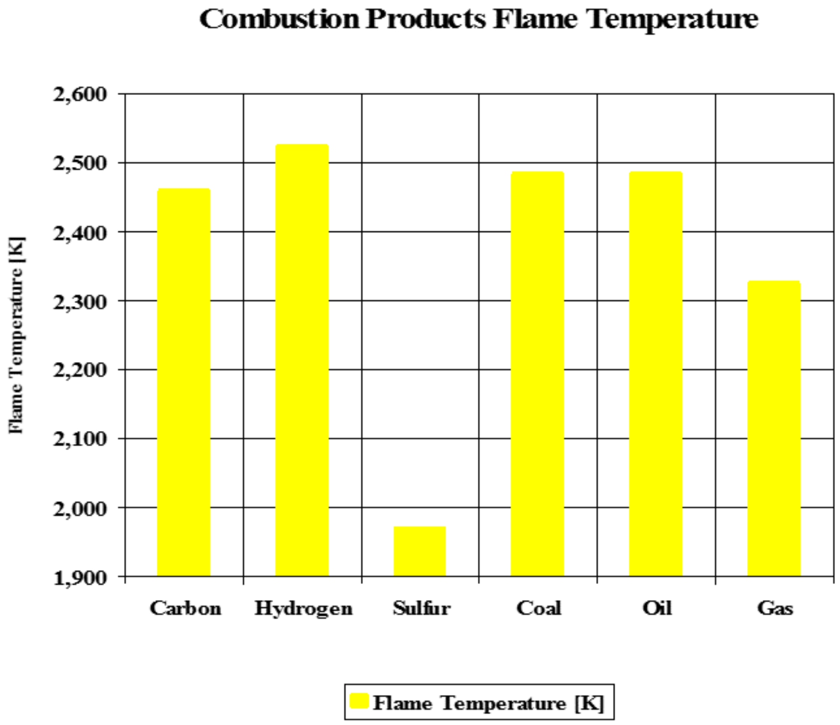
Figure 2 - Reactants and Combustion Products Species Specific Enthalpy vs Temperature



Combustion Products - Weight Basis

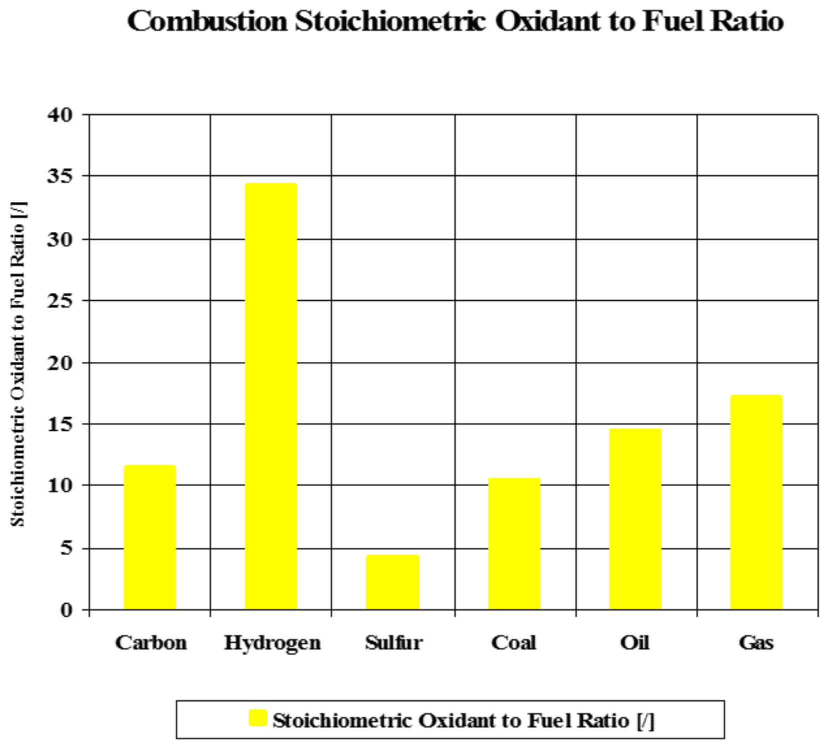


Combustion Products - Mole Basis



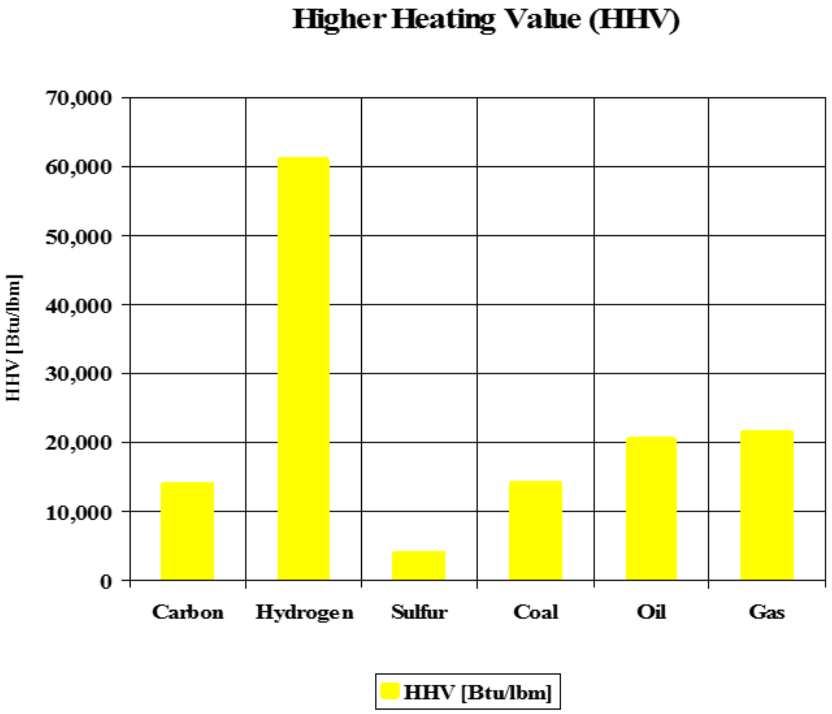
Fuel and Oxidant Inlet Temperature: 298 [K]

Combustion Products Flame Temperature



Fuel and Oxidant Inlet Temperature: 298 [K]

Combustion Stoichiometric Oxidant to Fuel Ratio



Fuel and Oxidant Inlet Temperature: 298 [K]

Higher Heating Value (HHV)

Conclusions

Hydrogen as the fuel has the highest flame temperature, requires the most mass amount of oxidant/air in order to have complete combustion per unit mass amount of fuel and has the largest fuel higher heating value.

When hydrogen reacts with oxidant/air, there is no CO_2 present in the combustion products.

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Expansion

This section provides an isentropic expansion analysis when the working fluid is air.

Analysis

In the presented expansion analysis, only air is considered as the working fluid behaving as a perfect gas -- specific heat has a constant value. Ideal gas state equation is valid -- pv = RT.

Air enters a turbine at point 1 and it exits the turbine at point 2. Isentropic expansion is considered with no entropy change.

Figure 1 presents an expansion schematic layout.

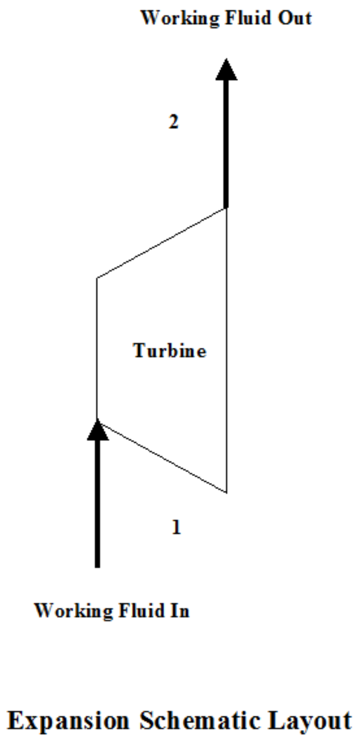


Figure 1 - Expansion Schematic Layout

Figure 2 presents an expansion temperature vs entropy diagram.

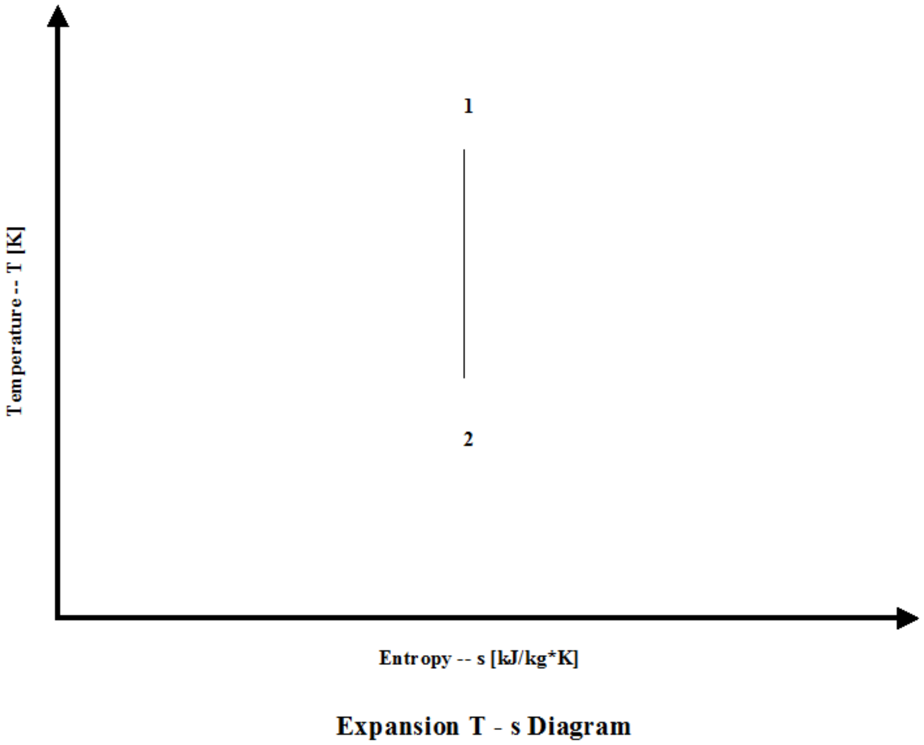
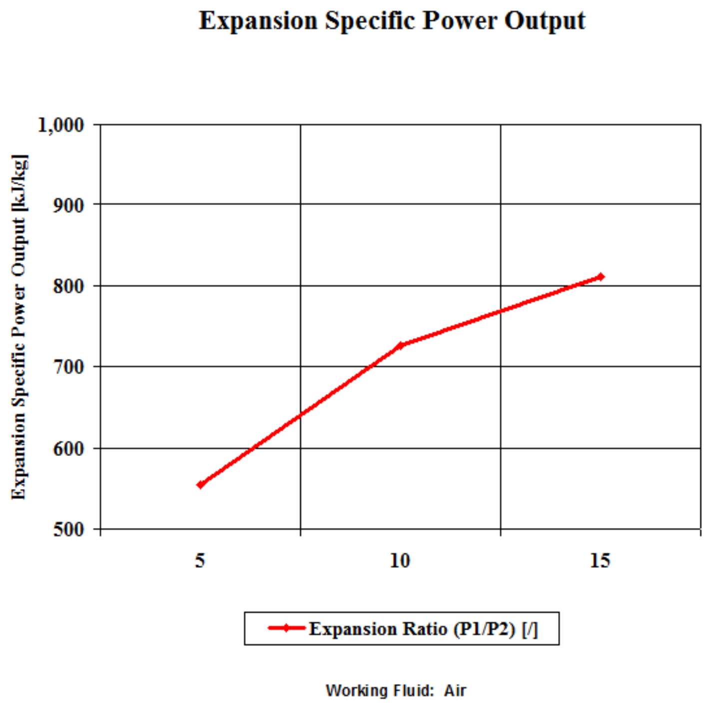


Figure 2 - Expansion Temperature vs Entropy Diagram

Figure 3 presents expansion specific power output values for a few typical expansion ratio values. It should be noted that the air enters the turbine at the temperature of 1,500 [K] and the turbine exhaust pressure is always equal to the standard ambient pressure -- 1 [atm] of absolute pressure.



Working Fluid: Air

Turbine Inlet Temperature: 1,500 [K]

Figure 3 - Expansion Specific Power Output

Figure 4 presents expansion power output values for two typical expansion ratio values and a few different working fluid mass flow rate values.

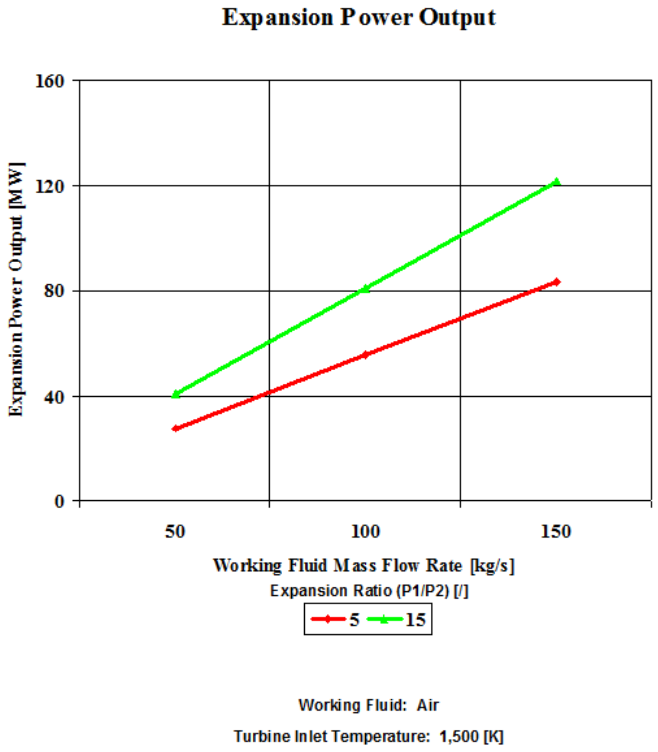


Figure 4 - Expansion Power Output

One can notice that both expansion specific power output and power output increase with an increase in the expansion ratio values. As the working fluid mass flow rate increases for a fixed expansion inlet temperature value, the expansion power output values increase too.

Assumptions

Working fluid is air. There is no friction and heat transfer. Expansion is isentropic -- there is no entropy change. Ideal gas state equation is valid -- pv = RT. Air behaves as a perfect gas -- specific heat has a constant value.

Power Cycle Components/Processes

Governing Equations

$$T_1/T_2 = (p_1/p_2)^{(\varkappa-1)/\varkappa}$$

$$\varkappa = c_p/c_v$$

$$c_p - c_v = R$$

$$pv = RT$$

$$w = c_p(T_1 - T_2)$$

$$W = c_p(T_1 - T_2)m$$

Input Data

T_1 = 1,500 [K]

p_1 = 5, 10 and 15 [atm]

p_2 = 1 [atm]

R = 0.2867 [kJ/kg*K]

c_p = 1.004 [kJ/kg*K]

$\varkappa = c_p/c_v$ - for air $\varkappa$ = 1.4 [/]

m = 50, 100 and 150 [kg/s]

Results

Specific Power Output vs Expansion Ratio
Expansion Inlet Temperature = 1,500 [K]

Expansion Ratio [/]	Specific Power Output [kW/kg/s]
5	555
10	726
15	811

Power Output vs Expansion Ratio for a few Mass Flow Rates
Expansion Inlet Temperature = 1,500 [K]

Power Output [MW]	**Mass Flow Rate [kg/s]**		
Expansion Ratio [/]	50	100	150
5	27.76	55.51	83.27
15	40.56	81.13	121.69

Conclusions

Both expansion specific power output and power output increase with an increase in the expansion ratio values. As the working fluid mass flow rate increases for a fixed expansion inlet temperaure, the expansion power output values increase too.

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