

PARAMETRIC ANALYSIS OF A COMBINED CYCLE POWER PLANT WITH COMPLETE COMBUSTION USING MATLAB GUI

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Abstract: Combined cycle is a common practice in power plants and used to obtain higher efficiency. It consists of a Rankine cycle connected to a Brayton cycle through a heat exchanger. Using a combined cycle instead of a single gas power cycle can boost up the overall efficiency of power plants up to 55%-60%. Combined cycle which is utilized in many industrial application is a one of the key elements of undergraduate thermodynamics education. In order to obtain realistic results about the thermal performance of the cycle, the thermodynamic model of the cycle needs to include combustion analysis rather than using air standard analysis. Thermodynamic analysis of a combustion process integrated in a cycle can be quite complex. Although there exist sophisticated commercial software products to handle those kind of simulations, these software products may be more complicated than necessary for undergraduate education, as well as require costly license fee. In this study, we have developed a simulation tool with a graphical user interface through MATLAB-GUI for the thermodynamic modeling of a combined cycle which may be quite useful for undergraduate thermodynamics education. The simulation tool allows students to perform parametric analysis for a combined cycle to investigate the effect of some input parameters on the cycle performance. The program uses `XSteam` function which is available through MathWorks Download Center for the determination of thermodynamic states of water, `XAir` function to obtain the thermodynamic properties of air (which was developed by our group), and `XGas` function which is developed through this study for the determination of the thermodynamic states of the gas products common in combustion processes.

Keywords: Combined Cycle, Combustion Analysis, MATLAB-GUI

MATLAB GUI KULLANILAN YANMA ANALİZİ İÇEREN PARAMETRİK KOMBİNE ÇEVİRİM ANALİZİ

Özet: Kombine çevrim, enerji santrallerinde yüksek verim sağlamak amacıyla yaygın olarak kullanılmaktadır. Kombine çevrim, Rankine ve Brayton çevrimlerinin bir ısı eşanjörü ile bağlanmasıyla oluşmaktadır. Kombine çevrim kullanımı, Brayton çevriminin tek başına kullanımına kıyasla verimi %55-%60 civarlarına çıkarabilmektedir. Endüstride yaygın olarak kullanılan bu çevrim, lisans eğitiminde de önemli bir yere sahiptir. Çevrim analiz edilirken daha gerçekçi sonuçlar alabilmek için, standart hava analizi yerine yanma analizinin yapılması gerekmektedir. Ancak bu hesaplamalar elle yapıldığında karmaşık olduğu ve uzun sürebildiği için öğrencilerin analiz yapmasını zorlaştırmaktadır. Bahsedilen analizi yapabilen lisanslı programlar bulunsa da bunlar kompleks ve pahalı programlar olduğu için lisans eğitiminde kullanılması pek mümkün olmamaktadır. Bu nedenle lisans eğitiminde kullanılmak üzere çeşitli parametrelerdeki değişimlerin sonuca olan etkisinin grafiksel sonuçlarla gözlemlenebileceği, kullanımı pratik olan bir kullanıcı arayüzü olan bir simülasyon aracı MATLAB-GUI kullanılarak geliştirilmiştir. Bu arayüz kullanıcıdan yakıt türü, çevrimin bazı noktalarındaki sıcaklık değerleri gibi girdileri aldıktan sonra genel çevrim analizini yapmakta ve çeşitli çıkış değerleri, genel verim gibi çıktıları sunmaktadır. Ayrıca parametrik analizin daha detaylı yapılabilmesi için bir parametre için verilen çeşitli değerlerin sonucu nasıl etkilediğini grafiksel olarak gösterebilmektedir. Program bu analizleri yaparken suyun termodinamik özelliklerini hesaplarken MathWorks Download Center'da açık kaynak olarak bulunabilen `XSteam` fonksiyonu, havanın termodinamik özelliklerini hesaplarken geçmişte grubumuz tarafından geliştirilen `XAir` fonksiyonunu ve yanma sonucu oluşan gazların termodinamik özelliklerini hesaplarken de bu çalışma kapsamında geliştirilen `XGas` fonksiyonunu kullanmaktadır.

Anahtar Kelimeler: Kombine Çevrim, Yanma Analizi, MATLAB, GUI

INTRODUCTION

Thermal power plants that work with fossil fuel produce 65% of the electricity in the world, even though more renewable, nuclear and hydroelectric energy power plants are built every day (Internet, 2017a). Therefore, it is still important to build more efficient energy conversion systems based on fossil fuels. Combined cycle power plants use fossil fuel (mostly natural gas) to produce power and they are one of the most efficient ways. Combined cycle consists of a Rankine cycle with a heat source from an exhaust gas of a Brayton cycle. The heat transfer is accomplished through a heat exchanger. The efficiency of both cycles is about 30% on natural gas and decreases to 25% with fuel oil. The main reason of low efficiency is the unused hot exhaust gas exiting from a Brayton cycle whose temperature can go up to 600°C (Internet, 2017b). Combined cycle is a subtle solution to increase the overall cycle efficiency. Combined cycle has many industrial applications which makes it a key element of undergraduate thermodynamics education.

It is typical that air standard analysis is used for the thermodynamic modeling of the combined cycle in undergraduate education. However, for more realistic results, the modeling of combustion processes in both cycles are crucial. Once the combustion processes are modeled, the combustion products which can be modeled as ideal gas mixtures can flow through the following components. Thermodynamic analysis of a combustion process integrated in a cycle can be quite complex. Although there exist sophisticated commercial software products to handle those kind of simulations, these software products may be more complicated than necessary for undergraduate education, as well as require costly license fee. In this study, we have developed a simulation tool with a graphical user interface through MATLAB-GUI for the thermodynamic modeling of a combined cycle which may be quite useful for undergraduate thermodynamics education. Previously, similar GUI developed by our group which utilize air-standard analysis for gas power cycles (Çağatay et al., 2013) and combined cycle (Coşkun et al., 2015). As a continuation of our previous work, we have included a complete combustion modeling for both cycles, and the flow of combustion products for the components following the combustors of both cycles. The thermodynamic properties of water are obtained using `XSteam` function which is available through MathWorks Download Center. The thermodynamic properties of air are obtained using `XAir` which was developed by our group. For the determination of thermodynamic properties of ideal gases present in the combustion products, `XGas` function is developed based on the following equations (Moran et al., 2015):

$$\Delta s = \int c_p \frac{dT}{T} \quad (1)$$

$$\Delta h = \int c_p dT \quad (2)$$

THERMODYNAMIC MODEL

Combined cycle forms of a Brayton cycle, a Rankine cycle and a heat exchanger in between to transfer the energy of the hot exhaust gas exiting the gas turbine, to the stream entering the steam turbine, which acts as the steam generator of a typical Rankine cycle (Figure 1). The thermodynamic model for the combined cycle is studied in two parts as Brayton and Rankine cycles (Çengel and Boles (2005); Moran et al. (2015)). Air standard model is one of the most common models used in thermodynamic analysis of gas power systems. It is a simplification to conduct elementary thermodynamic analysis for the chosen system. It has the following principles (Moran et al., 2015):

- A fixed amount of air modeled as an ideal gas is the working fluid.
- The combustion process is replaced by a heat transfer from an external source.

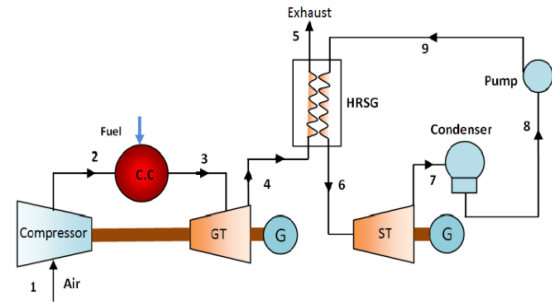


Figure 1. Schematic diagram of a combined cycle power plant

Generally, this approach is used while analyzing a Brayton cycle but including combustion analysis gives a more accurate result than air standard analysis. For the combustion analysis at the combustor of the Brayton cycle, complete combustion analysis is conducted to provide the molar rates of the combustion products; given the fuel and the percentage of theoretical air. To analyze the Brayton cycle, the first law of thermodynamics is applied to each state. The T-s diagram obtained from the analysis is given in Figure 2.

Compression ratio, molar flow rate of fuel, fuel temperature, ambient temperature and pressure, turbine inlet temperature and exhaust gas temperature and pressure values can be edited in the model. The isentropic efficiencies for compressor and turbines are also editable parameters and initially given in the range of 85 to 90% (Rahman et al., 2011 a). A function called `XGas` is developed and used to determine the specific enthalpy and specific entropy values of the gases that

are used in combustion analysis for given temperature and pressure values. Furthermore, XAir function, which was developed by our group, is utilized to determine the specific enthalpy and specific entropy values of air given the temperature and pressure values.

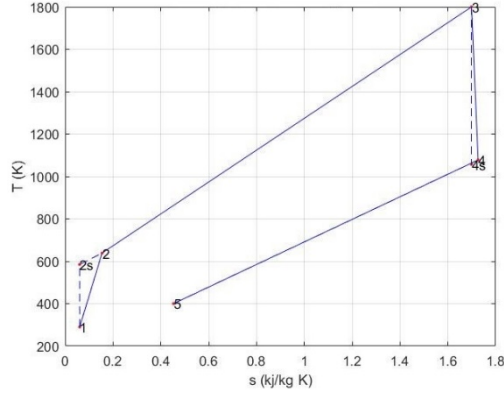


Figure 2. Brayton Cycle T-s Diagram

State 1 (Compressor Inlet): The ambient temperature and pressure are input parameters, so other thermodynamic properties are determined by XAir function.

State 2a (Combustor Inlet -Air): The combustor pressure is calculated directly from the compression ratio. For the enthalpy of the State 2, the definition of the isentropic efficiency of the compressor is used as:

$$h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_c} \quad (3)$$

where “2s” stands for the isentropic state of the compressor exit. Knowing the pressure and the enthalpy of State 2, other thermodynamic properties are evaluated using XAir.

State 2f (Combustor Inlet -Fuel): The temperature and pressure values for the fuel at the combustor inlet are input parameters, and other thermodynamic properties are determined by XGas function.

State 3 (Gas Turbine Inlet): For the mixture at the inlet of gas turbine, the mole fractions of the combustion products are found by equalizing the chemical equation. Then, the specific enthalpy values of every single gas in the products mixture are obtained from XGas function for known temperature and pressure values. Specific enthalpy and entropy values of the mixture are found from the following formula:

$$h = \sum_i y_i \bar{h}_i M_i \quad (4)$$

State 4 (Heat Exchanger Inlet): Pressure value for State 4 is same as State 5, where air is discharged to

atmosphere and the pressure is equal to 1 atm. For the enthalpy of the State 4, the definition of the isentropic efficiency of the compressor is used as:

$$h_4 = h_3 - \eta_t(h_3 - h_{4s}) \quad (5)$$

where “4s” stands for the isentropic state of the compressor exit. Knowing the pressure and the enthalpy of State 4, other thermodynamic properties are evaluated using XAir.

State 5 (Heat Exchanger Outlet): With the given values of pressure and temperature for exhaust discharge state, XGas is used to obtain the other thermodynamic properties of the ideal gas mixture.

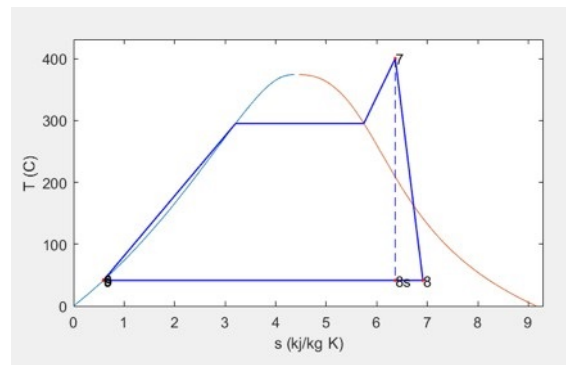


Figure 3. Rankine Cycle T-s Diagram

To analyze the Rankine cycle, the first law of thermodynamics is applied to each state. The T-s diagram obtained from the analysis is given in Figure 3. Steam turbine inlet temperature, quality of the stream exiting the condenser and the pressures are input parameters. The heat exchanger is assumed to be adiabatic and to be able to transfer all of the heat obtained from the exhaust of the gas turbine to the inlet of the steam turbine, which is quite a realistic assumption considering the negligible heat loss from this heat exchanger compared to the heat exchange between the fluids. The isentropic efficiency of the pump is also an input parameter, and it is initially set as %80 since the typical pump efficiency is around %75 - %85 (Turns, 2006). The turbine efficiency is also an input parameter, and it is in the range of 85 to 90% (Rahman et al., 2011 b). XSteam function is utilized for the determination of the thermodynamics properties of water.

State 7 (Steam Turbine Inlet): The temperature and pressure value are input parameters so the other values are determined by XSteam.

State 8 (Condenser Inlet): The pressure of this state is given as an input. For the enthalpy of the State 8, the definition of the isentropic efficiency of the turbine is used as:

$$h_8 = h_7 - \eta_t(h_7 - h_{8s}) \quad (6)$$

where “8s” stands for the isentropic state of the compressor exit. Knowing the pressure and the enthalpy of State 8, other thermodynamic properties are evaluated using XSteam.

State 9 (Pump Inlet): The State 9 is taken as saturated liquid, which is a typical case in real applications. For this state, the pressure is known since condenser pressure is given, so the properties are obtained through XSteam.

State 6 (Heat Exchanger Inlet): The pressure of this state is given as a user input of heat exchanger pressure for water side. For the enthalpy of the State 6, the definition of the isentropic efficiency of the pump is used as:

$$h_6 = h_9 + \frac{h_{6s} - h_9}{\eta_p} \quad (7)$$

where “6s” stands for the isentropic state of the compressor exit. Knowing the pressure and the enthalpy of State 6, other thermodynamic properties are evaluated using XSteam.

After all of the states are fixed, the mass flow rate of the Rankine cycle can be determined by applying energy balance to the heat exchanger:

$$\dot{m}_{rankine}(h_7 - h_6) = \dot{m}_{brayton}(h_4 - h_5) \quad (8)$$

Finally, in order to calculate overall cycle efficiency, net power output and the heat transfer rate of the combustor are obtained with the following relations:

$$\dot{W}_{net} = \dot{W}_{gt} + \dot{W}_{st} - \dot{W}_c - \dot{W}_p \quad (9)$$

$$\dot{W}_{gt} = \dot{m}_{brayton}(h_3 - h_4) \quad (10)$$

$$\dot{W}_{st} = \dot{m}_{rankine}(h_7 - h_8) \quad (11)$$

$$\dot{W}_c = \dot{m}_{air}(h_{2a} - h_1) \quad (12)$$

$$\dot{W}_p = \dot{m}_{rankine}(h_6 - h_9) \quad (13)$$

$$\dot{Q}_{in} = \dot{m}_{brayton}(h_3 - h_2) \quad (14)$$

$$\eta = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \quad (15)$$

RESULTS AND DISCUSSION

The developed user interface asks for some input parameters from the user and displays the outputs selected by the user. The screenshot of the user interface is given in Figure 4.

Figure 4. MATLAB-GUI Interface

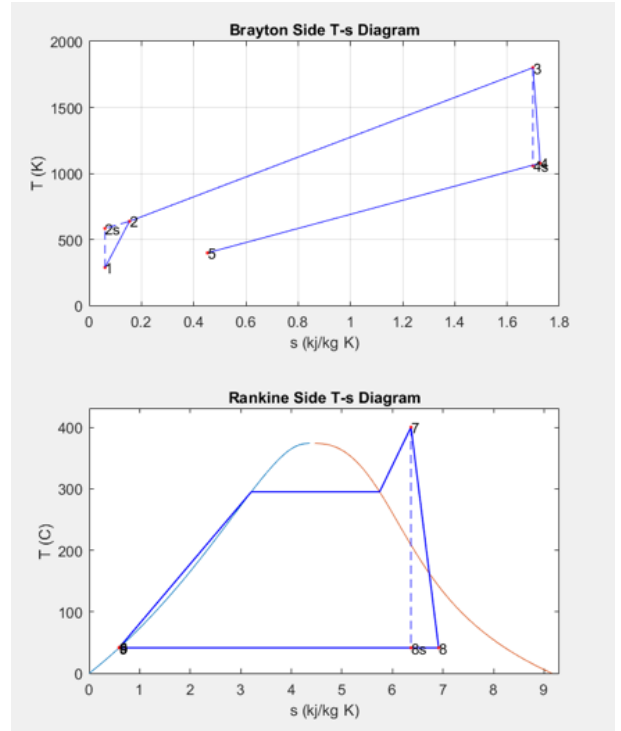


Figure 5. Brayton and Rankine cycle T-s diagram

The output options that the user can display are T-s diagrams of Rankine and Brayton sides of the cycle, overall cycle efficiency and thermo-dynamic properties of states, compression ratio etc. efficiency graph, fuel inlet temperature vs. efficiency graph and fuel type vs. efficiency graph. The user can check the desired output, and it will be displayed on the right-hand side display of the interface screen. This program helps the user to analyze a combined cycle power plant step by step with the all values and T-s diagrams. Since the program uses

user inputs to calculate, the user can modify the cycle and interpret the differences.

If T-s diagrams are selected as outputs, the user can change the parameters and see the outcome of those changes in the T-s diagrams of the cycle. It can supply the students the qualitative information about T-s diagrams of combined cycle when combustion is also taken into account instead of air-standard analysis. The output T-s diagrams of both cycles are given in Figure 5. If overall cycle efficiency and thermodynamic properties of states are selected as the output to be displayed, the user can change the parameters and see the outcome of those changes in overall cycle efficiency and thermodynamic properties of states such as Brayton turbine exit temperature or enthalpy value of any state.

If the compression ratio vs. overall cycle efficiency graph is selected to be displayed, as it can be seen in Figure 6, aside from the general parameters, the user can change the compression ratio parameter under the graph to see the changes on the efficiency. This provides the user to understand the effect of compression ratio on overall cycle efficiency effectively.

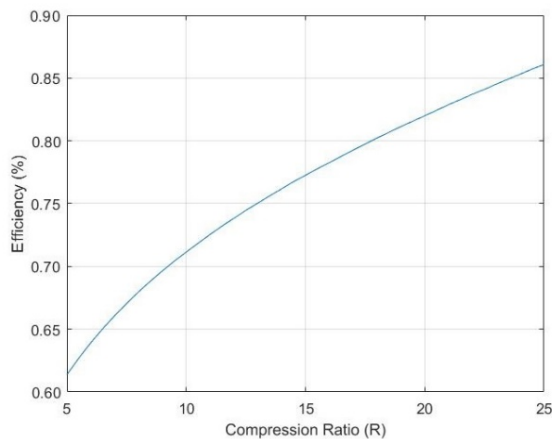


Figure 6. Compression ratio on overall efficiency

If other output options such as ambient temperature or fuel inlet temperature vs. overall cycle efficiency are selected to be displayed, the user can again change those temperature parameters and see their effects on overall cycle efficiency, as it is on compression ratio. It can provide the user a general idea about the effect of those parameters on overall cycle efficiency. An example run of the interface for the output option of ambient temperature (Internet, 16 Jan. 2017c) vs. overall cycle efficiency and fuel inlet temperature vs. overall cycle efficiency displays are shown in the Figures 7 and 8.

In both graphs, general input values that are given on the left-hand side of the interface screen are held constant and merely the efficiency for different temperatures are given on the graphs. The fact that the change of ambient temperature has a greater effect on

the efficiency than the effect of fuel inlet temperature can be seen from the analysis. This run of the interface is an example of how those outputs can help the user to understand the effect of some parameters on the overall cycle efficiency.

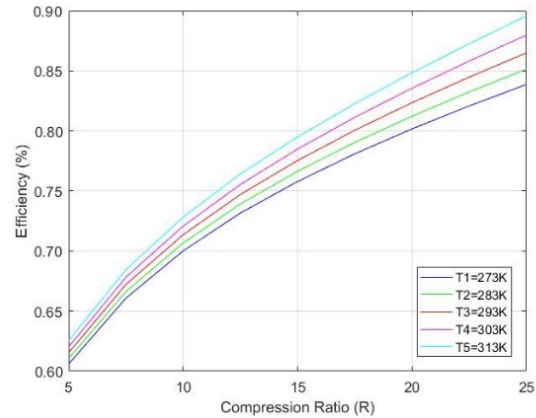


Figure 7. Effect of ambient temperature on compression ratio vs. efficiency

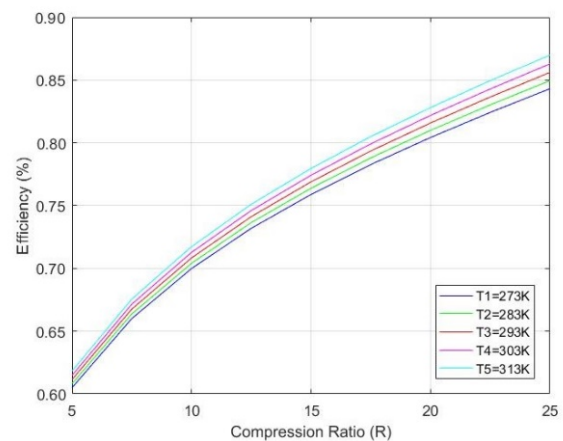


Figure 8. Effect of fuel inlet temperature on compression ratio vs. efficiency

CONCLUSIONS

The aim of this study is to develop a graphical user interface to help undergraduate students have a better understanding of a combined cycle with combustion analysis. The concept of complete combustion is successfully implemented. However, one should note that since the c_p tables used for thermodynamic properties of the combustion products are valid up to 1800 K, the accuracy of the created model is questionable beyond that temperature. Furthermore, for an adiabatic combustion process, the temperature value of the products almost always exceeds the mentioned limits of 1800K, so adiabatic combustion is not assumed and a heat loss at the combustor is introduced so that the temperature of the products is inside the range of the model, below 1800K. Because of this assumption, the

model may have become more of a qualitative model than a quantitative one. However, it still fulfills the aim of giving a better understanding of a combined cycle with combustion to the user, qualitatively. Inclusion of more reliable data into the model will be the future research direction to improve the model to make it more realistic.

NOMENCLATURE

\dot{Q} :	Heat transfer rate [kW]
\dot{W} :	Power [kW]
\dot{m} :	Mass flow rate [kg / s]
h :	Specific enthalpy [kJ / kg]
P :	Pressure [MPa]
s :	Specific entropy [kJ / kg K]
T :	Temperature [K]
u :	Specific internal energy [kJ / kg]
x :	Quality
R :	Compressibility ratio
η :	Thermal efficiency
c_p :	Specific heat capacity

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APPENDIX

Table 1. c_p ideal-gas specific heats of various common gases: as a function of temperature (Kyle, 1984).

$\bar{c}_p = a + b \times T + c \times T^2 + d \times T^3$ (T in K, c_p in kJ/kmol * K)								
Substance	Formula	a	b	c	d	Temperature range, K	Max. %error	Avg. %error
Nitrogen	N ₂	28.90	-0.1571 x 10 ⁻²	0.8081 x 10 ⁻⁵	-2.873 x 10 ⁻⁹	273-1800	0.59	0.34
Oxygen	O ₂	25.48	1.520 x 10 ⁻²	-0.7155 x 10 ⁻⁵	1.312 x 10 ⁻⁹	273-1800	1.19	0.28
Air	-	28.11	0.1967 x 10 ⁻²	0.4802 x 10 ⁻⁵	-1.966 x 10 ⁻⁹	273-1800	0.72	0.33
Hydrogen	H ₂	29.11	-0.1916 x 10 ⁻²	0.4003 x 10 ⁻⁵	-0.8704 x 10 ⁻⁹	273-1800	1.01	0.26
Carbon monoxide	CO	28.16	0.1675 x 10 ⁻²	0.5372 x 10 ⁻⁵	-2.222 x 10 ⁻⁹	273-1800	0.89	0.37
Carbon dioxide	CO ₂	22.26	5.981 x 10 ⁻²	-3.501 x 10 ⁻⁵	7.469 x 10 ⁻⁹	273-1800	0.67	0.22
Water vapor	H ₂ O	32.24	0.1923 x 10 ⁻²	1.055 x 10 ⁻⁵	-3.595 x 10 ⁻⁹	273-1800	0.53	0.24
Acetylene	C ₂ H ₂	21.8	9.2143 x 10 ⁻²	-6.527 x 10 ⁻⁵	18.21 x 10 ⁻⁹	273-1500	1.46	0.59
Benzene	C ₆ H ₆	-36.22	48.475 x 10 ⁻²	-31.57 x 10 ⁻⁵	77.62 x 10 ⁻⁹	273-1500	0.34	0.20
Methanol	CH ₄ O	19.0	9.152 x 10 ⁻²	-1.22 x 10 ⁻⁵	-8.039 x 10 ⁻⁹	273-1500	0.18	0.08
Ethanol	C ₂ H ₆ O	19.9	20.96 x 10 ⁻²	-10.38 x 10 ⁻⁵	20.05 x 10 ⁻⁹	273-1500	0.40	0.22
Methane	CH ₄	19.89	5.024 x 10 ⁻²	1.269 x 10 ⁻⁵	-11.01 x 10 ⁻⁹	273-1500	1.33	0.57
Ethane	C ₂ H ₆	6.900	17.27 x 10 ⁻²	-6.406 x 10 ⁻⁵	7.285 x 10 ⁻⁹	273-1500	0.83	0.28
Propane	C ₃ H ₈	-4.04	30.48 x 10 ⁻²	-15.72 x 10 ⁻⁵	31.74 x 10 ⁻⁹	273-1500	0.40	0.12
Ethylene	C ₂ H ₄	3.95	15.64 x 10 ⁻²	-8.344 x 10 ⁻⁵	17.67 x 10 ⁻⁹	273-1500	0.54	0.13