Brayton Cycle Compare & Solve: A New Tool for Analysis and Comparison of Brayton Cycle Engines

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Louis Christensen & Randall Mathison
The Ohio State University Gas Turbine Laboratory

Abstract

The air-breathing Brayton cycle is widespread throughout power generation and propulsion systems, making it a fundamental part of every mechanical or aerospace engineering student's repertoire. Students are introduced to cycle analysis in thermodynamics courses and may see more in-depth coverage of the cycle for gas turbine applications in advanced technical elective courses. When being pushed to design rather than analyze an engine, students need to be able to compare their engine designs and make sense of the effects different changes have on the overall engine performance. The solution to enable this in a course is a lightweight cycle simulator. For the software tool to be successful in a classroom, it needs to be intuitive, quick to set up, and accurate. These requirements are met in the creation of a gas turbine engine simulator, Brayton Cycle: Compare & Solve (BCCS). In a MATLAB App, the user specifies numerous engine parameters and the tool performs complete thermodynamic design point analysis of the engine. Built-in tools enable the user to analyze engine performance, thermodynamic properties, temperature-entropy diagram, and pressure-volume diagram. Most importantly, the solver records the results, so multiple engines can be solved and compared simultaneously. Users can make small changes to an engine and instantly see the impact.

BCCS was integrated into an existing propulsion course at The Ohio State University in spring of 2020. There was a class lecture introducing the tool along with a homework assignment that challenged students to evaluate different engine designs. The effectiveness of and student response to the tool are evaluated using detailed analysis of student homework submissions and the Student Response to Instructional Practices tool [8]. Students achieved the desired learning objectives, and all commented that BCCS was a valuable addition to the course.

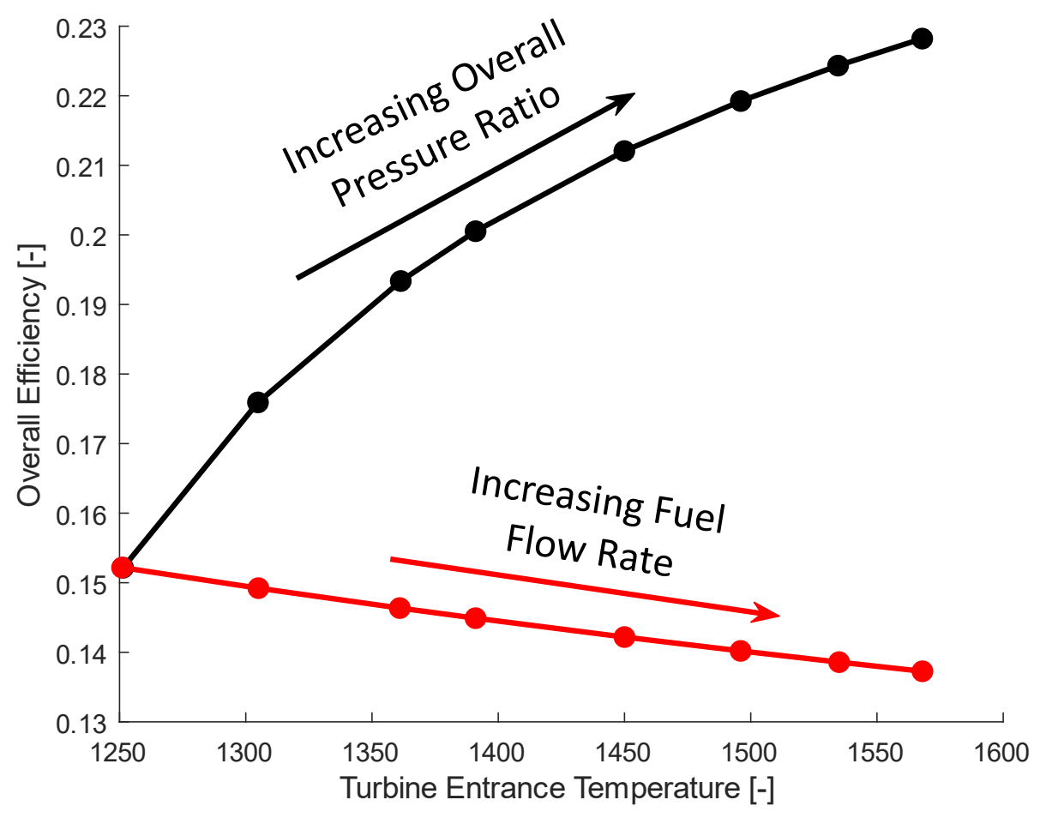
Sample Lesson

Problem: How should we increase turbine entry temperature?

Approach: Increase overall pressure ratio or increase the amount of fuel being burned.

Advantages:
- Students explore what parameters affect the turbine entrance temperature.
- They can discover the trends on their own instead of being told what happens (active learning)

Solution: Increase the overall pressure ratio

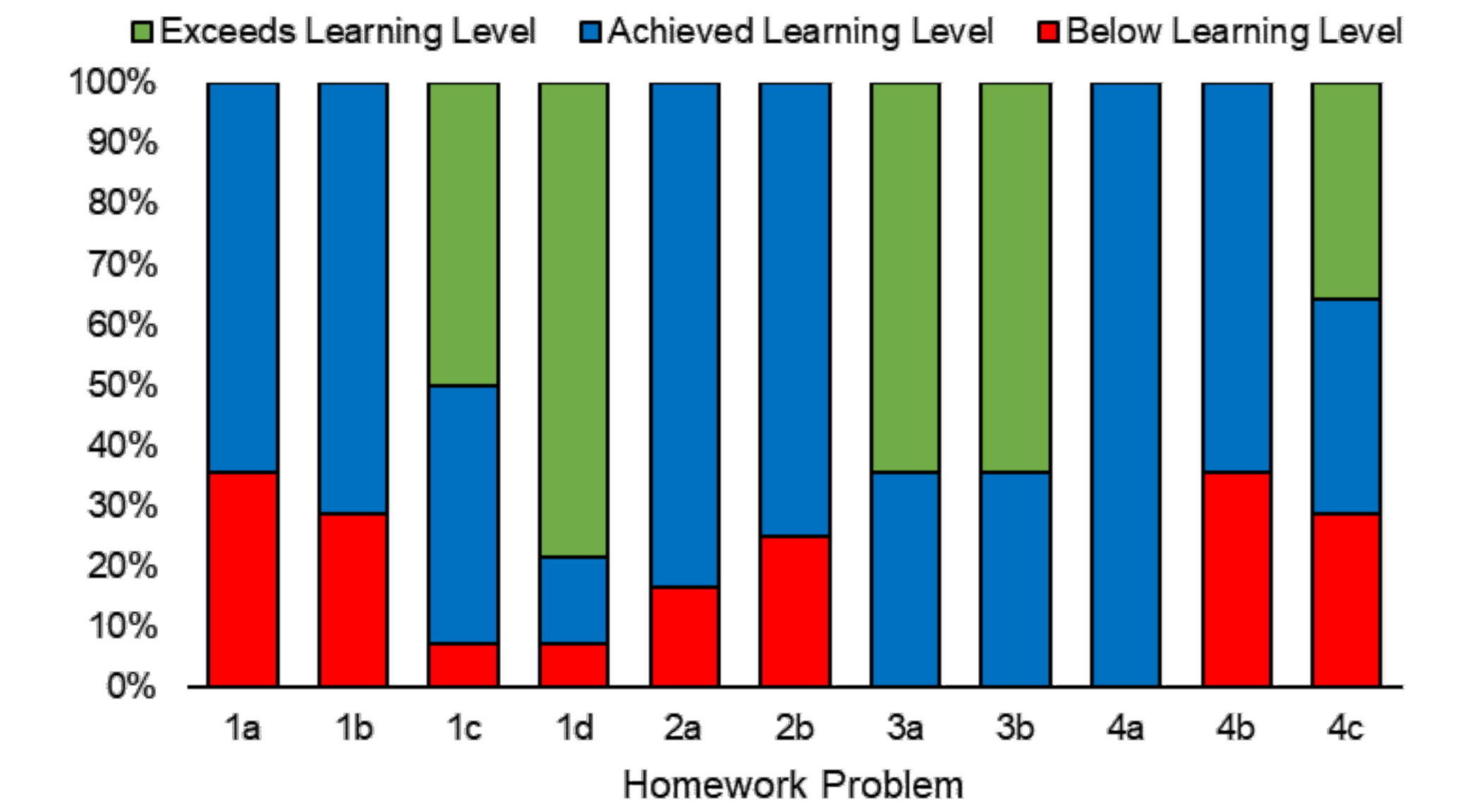


Classroom Response

Summary of survey results on a 5-point scale

Instrument Item	Mean	Mode	Min	Max
Value				
The degree to which students feel the activity is worthwhile	4.01	4	2	5
Positivity				
How positive or negative the students feel towards the activity	4.00	4	1	5
Participation				
The extent to which students participate or demonstrate resistance	3.48	4	1	5
Evaluation				
How the students rate the instructor of the course	4.46	5	2	5

- Students unanimously felt BCCS is a valuable addition to the course.
- Some students were using the software in class and asking questions during lecture
- Students met or exceeded learning goals on homework
- Students indicated increased understanding of the Brayton cycle



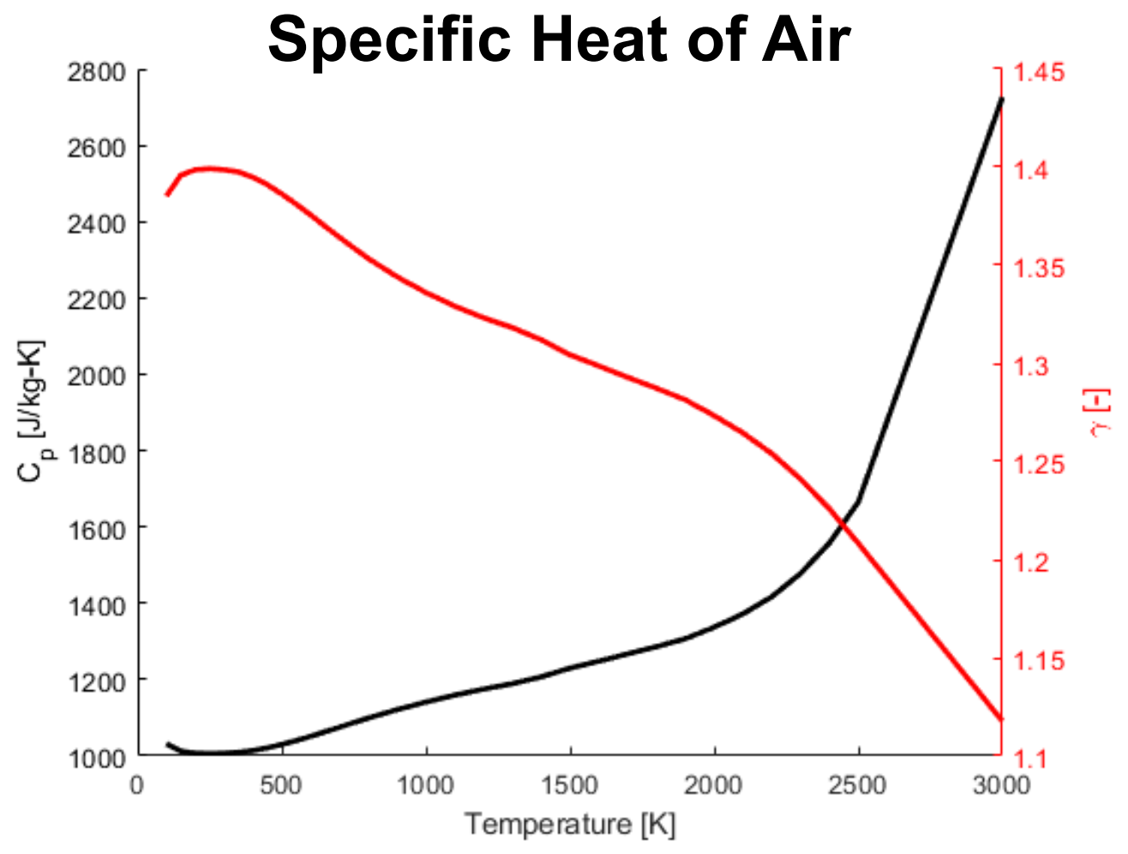
Student performance on the BCCS homework

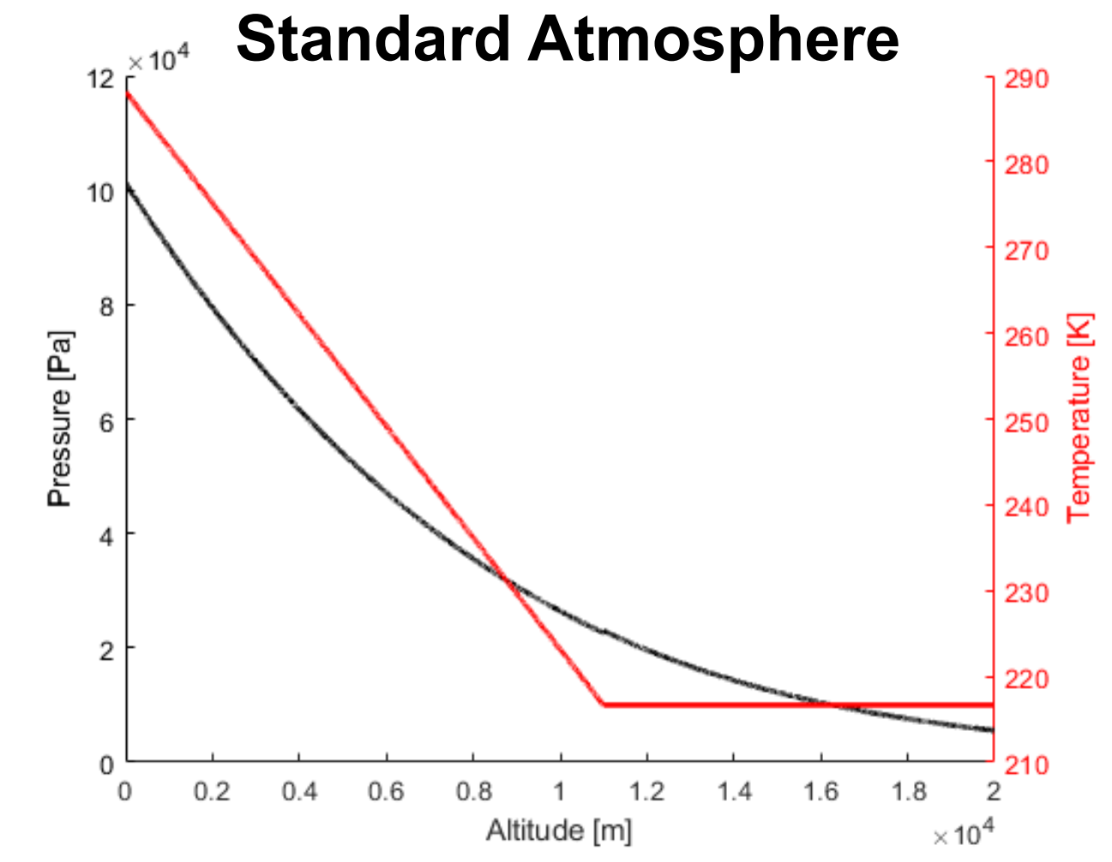
Features at a Glance

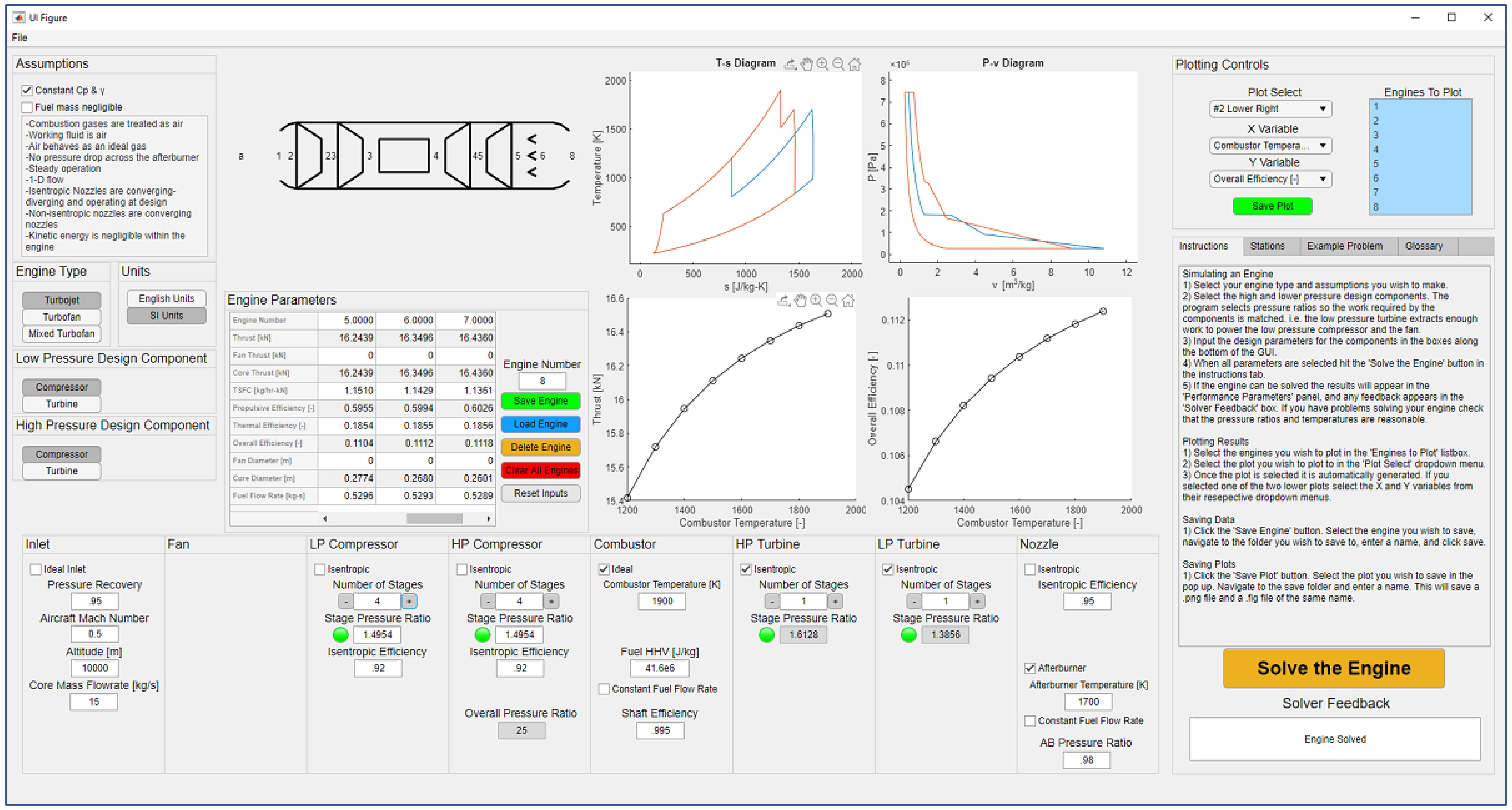
- 1-D Brayton Cycle Solver
- 45 user inputs
- Solve 3 different engine layouts
- Instantaneous solutions
- Stores data of solved engines
- Built-in plotter
- Save/Load and share engines
- Designed as a MATLAB App compatible with R2016a and newer
- Available for free at https://gtl.osu.edu/brayton-cycle-compare-solve-bccs or the MATLAB file exchange under "BCCS"

Plotting

- T-s diagram
- P-v diagram
- Two customizable plots to instantly compare engine designs
- Built in standard atmosphere and air specific heat plots [5-6]
- Save plots to share your findings







Assumptions

☑ Constant Cp & γ
☐ Fuel mass negligible

-Combustion gases are treated as air
-Working fluid is air
-Air behaves as an ideal gas
-No pressure drop across the afterburner
-Steady operation
-1-D flow
-Isentropic Nozzles are converging-diverging and operating at design
-Non-isentropic nozzles are converging nozzles
-Kinetic energy is negligible within the engine

Engine Type: Turbojet / Turbofan / Mixed Turbofan

Units: English Units / SI Units

Low Pressure Design Component: Compressor / Turbine

High Pressure Design Component: Compressor / Turbine

Engine Parameters

Engine Number	5.0000	6.0000	7.0000
Thrust [kN]	16.2439	16.3496	16.4360
Fan Thrust [kN]	0	0	0
Core Thrust [kN]	16.2439	16.3496	16.4360
TSFC [kg/hr-kN]	1.1510	1.1429	1.1361
Propulsive Efficiency [-]	0.5955	0.5994	0.6026
Thermal Efficiency [-]	0.1854	0.1855	0.1856
Overall Efficiency [-]	0.1104	0.1112	0.1118
Fan Diameter [m]	0	0	0
Core Diameter [m]	0.2774	0.2680	0.2601
Fuel Flow Rate [kg-s]	0.5296	0.5293	0.5289

Engine Number: 8

Plotting Controls

Plot Select: #2 Lower Right
X Variable: Combustor Tempera...
Y Variable: Overall Efficiency [-]
Engines To Plot: 1 2 3 4 5 6 7 8

Simulating an Engine
1) Select your engine type and assumptions you wish to make.
2) Select the high and lower pressure design components. The program selects pressure ratios so the work required by the components is matched. i.e. the low pressure turbine extracts enough work to power the low pressure compressor and the fan.
3) Input the design parameters for the components in the boxes along the bottom of the GUI.
4) When all parameters are selected hit the 'Solve the Engine' button in the instructions tab.
5) If the engine can be solved the results will appear in the 'Performance Parameters' panel, and any feedback appears in the 'Solver Feedback' box. If you have problems solving your engine check that the pressure ratios and temperatures are reasonable.

Plotting Results
1) Select the engines you wish to plot in the 'Engines to Plot' listbox.
2) Select the plot you wish to plot to in the 'Plot Select' dropdown menu.
3) Once the plot is selected it is automatically generated. If you selected one of the two lower plots select the X and Y variables from their resepective dropdown menus.

Saving Data
1) Click the 'Save Engine' button. Select the engine you wish to save, navigate to the folder you wish to save to, enter a name, and click save.

Saving Plots
1) Click the 'Save Plot' button. Select the plot you wish to save in the pop up. Navigate to the save folder and enter a name. This will save a .png file and a .fig file of the same name.

Solver Feedback: Engine Solved

Inlet
☐ Ideal Inlet
Pressure Recovery: .95
Aircraft Mach Number: 0.5
Altitude [m]: 10000
Core Mass Flowrate [kg/s]: 15

Fan

LP Compressor
☐ Isentropic
Number of Stages: 4
Stage Pressure Ratio: 1.4954
Isentropic Efficiency: .92

HP Compressor
☐ Isentropic
Number of Stages: 4
Stage Pressure Ratio: 1.4954
Isentropic Efficiency: .92
Overall Pressure Ratio: 25

Combustor
☑ Ideal
Combustor Temperature [K]: 1900
Fuel HHV [J/kg]: 41.6e6
☐ Constant Fuel Flow Rate
Shaft Efficiency: .995

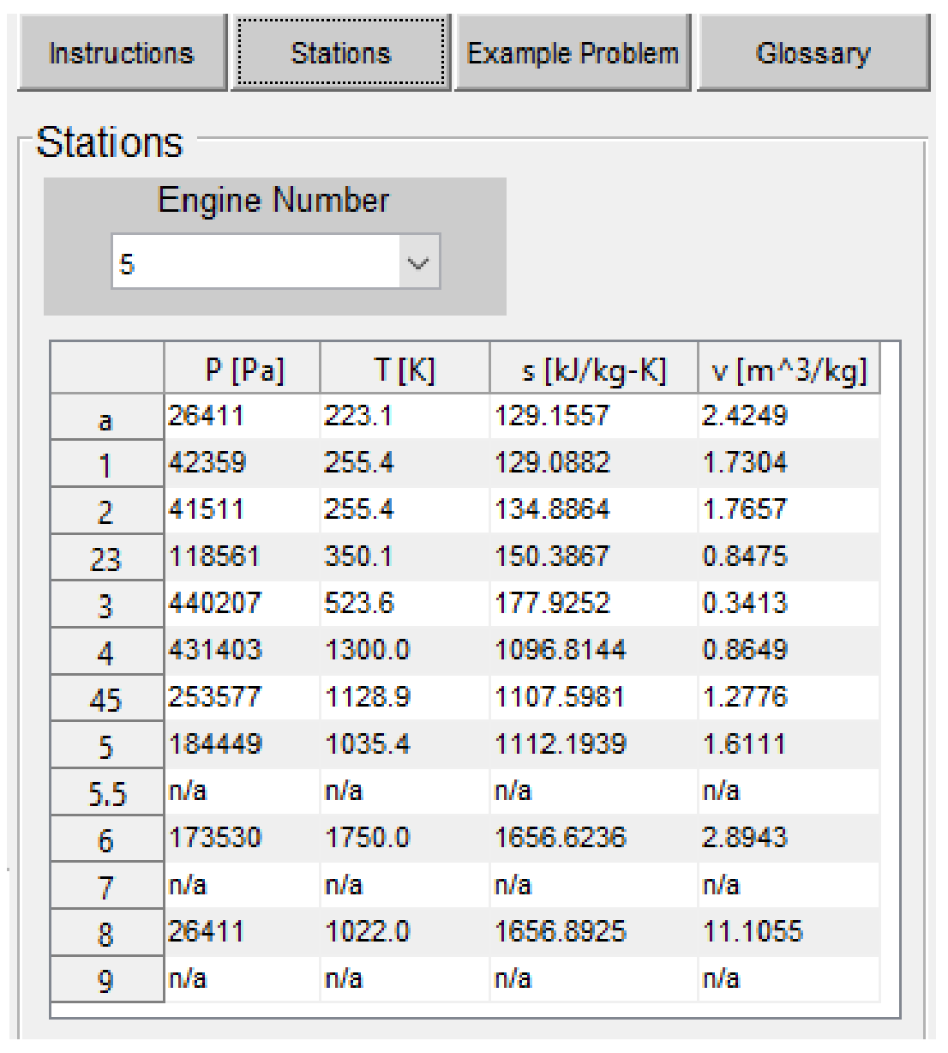
HP Turbine
☑ Isentropic
Number of Stages: 1
Stage Pressure Ratio: 1.6128

LP Turbine
☑ Isentropic
Number of Stages: 1
Stage Pressure Ratio: 1.3856

Nozzle
☐ Isentropic
Isentropic Efficiency: .95
☑ Afterburner
Afterburner Temperature [K]: 1700
☐ Constant Fuel Flow Rate
AB Pressure Ratio: .98

Thermodynamic Properties

- View thermodynamic properties pressure, temperature, specific entropy, and specific volume at each labeled engine station
- Verified using *Fundamentals of Jet Propulsion* [7]



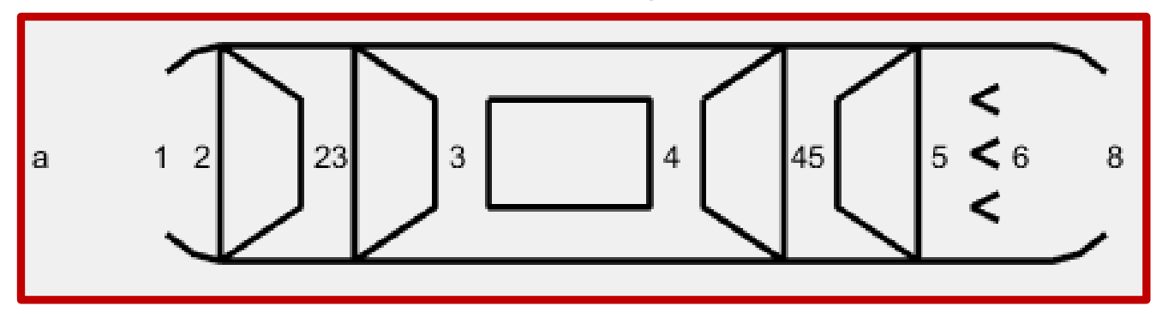
Stations

Engine Number: 5

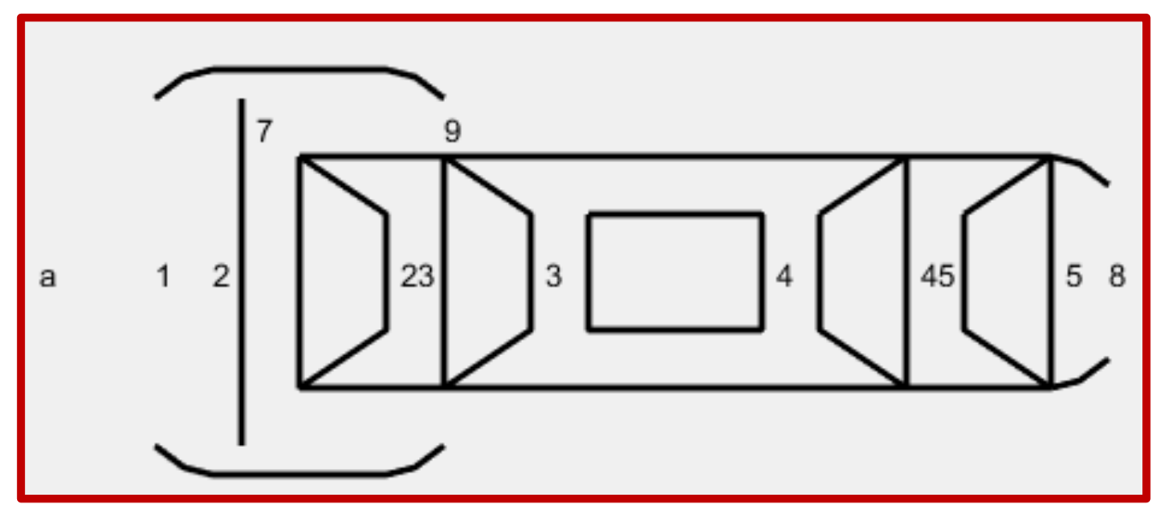
	P [Pa]	T [K]	s [kJ/kg-K]	v [m^3/kg]
a	26411	223.1	129.1557	2.4249
1	42359	255.4	129.0882	1.7304
2	41511	255.4	134.8864	1.7657
23	118561	350.1	150.3867	0.8475
3	440207	523.6	177.9252	0.3413
4	431403	1300.0	1096.8144	0.8649
45	253577	1128.9	1107.5981	1.2776
5	184449	1035.4	1112.1939	1.6111
5.5	n/a	n/a	n/a	n/a
6	173530	1750.0	1656.6236	2.8943
7	n/a	n/a	n/a	n/a
8	26411	1022.0	1656.8925	11.1055
9	n/a	n/a	n/a	n/a

Supported Engine Types

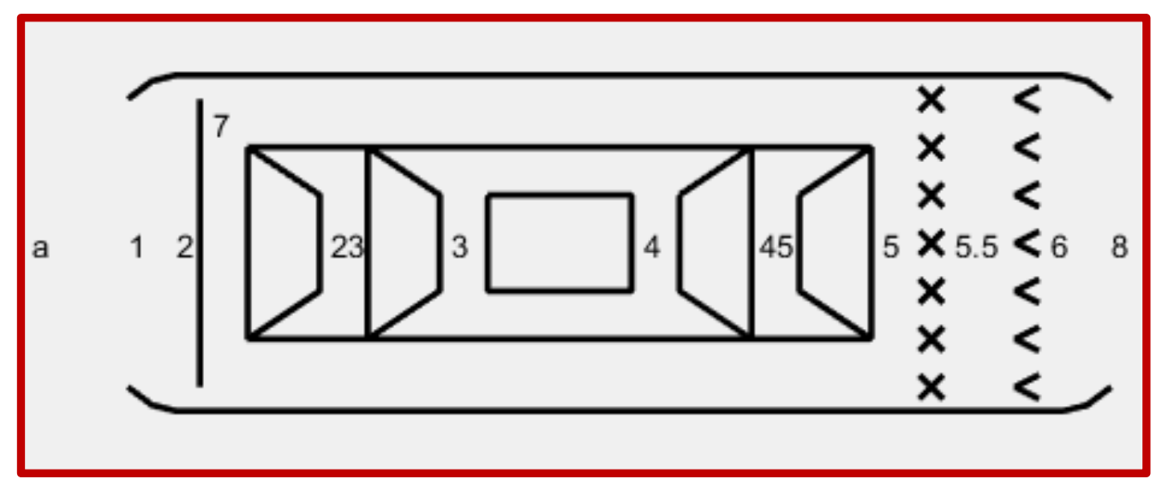
Turbojet



Turbofan



Mixed Turbofan



Comparable Software

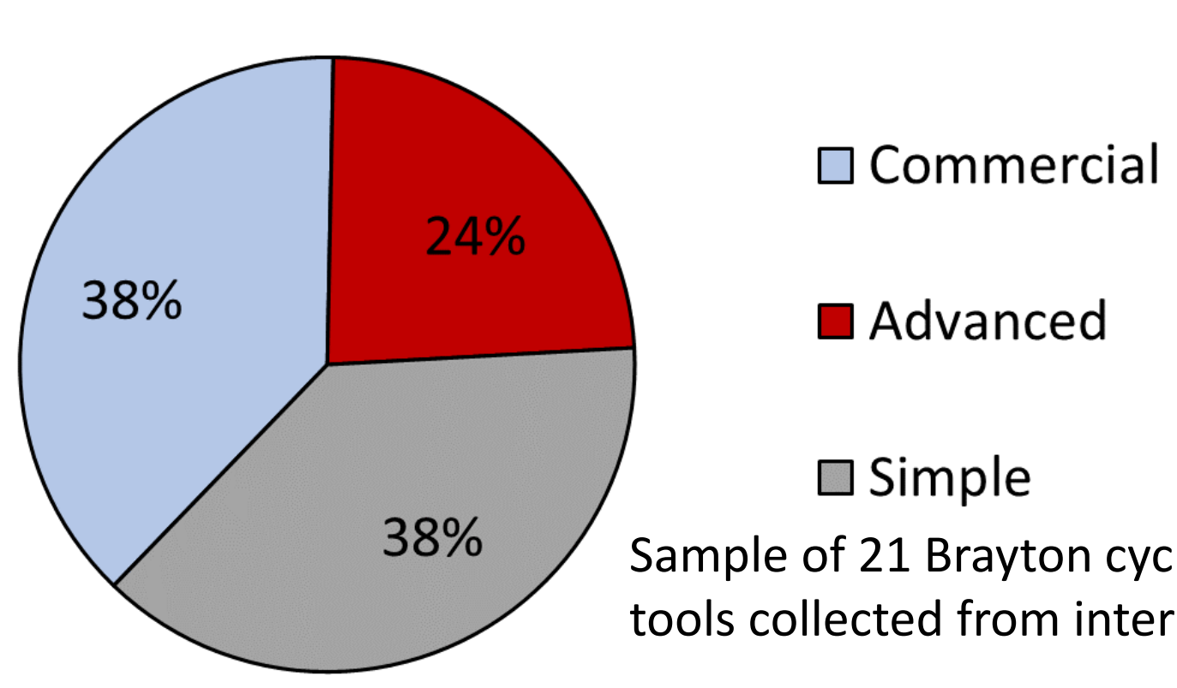
BCCS fills a niche for an advanced tool that allows users to compare results

Commercial: Complex tools meant to design and analyze complete engines usually incorporating features such as geometry design, off design performance, or engine control. Examples include Gasturb13, MDIDS-GT, or NPSS [1-3]

Advanced: More complex tools built for educational purposes or specialization in a particular area such as off-design performance or plotting, The scope of these programs is intentionally limited. Examples include AeroEngineS or BCCS [4]

Simple: Analysis tools with minimal user input and little to no learning curve. Ideal analysis only

Solver Types



Sample of 21 Brayton cycle simulation tools collected from internet searches

Works Cited

[1] Kurzke, J., "GasTurb 13," *GasTurb*, (2020) URL http://www.gasturb.de/.

[2] Kidikian, J., "MDIDS-GT," (2019) URL https://sites.google.com/site/mdidsgt/home.

[3] Krouse, C., "Numerical Propulsion System Simulation (NPSS)," (2019) URL https://www.swri.org/consortia/numerical-propulsion-system-simulation-npss.

[4] Pontika, E. C., Kalfas, A. I., and Aslanidou, I., "AeroEngineS: Multi-Platform Application for Aero Engine Simulation and Compressor Map Operating Point Prediction," *Proc. ASME Turbo Expo 2019 Turbomach. Tech. Conf. Expo.*, Phoenix, (2019) DOI 10.1115/GT2019-91961.

[5] Incropera, F. P., Dewitt, D. P., Bergman, T. L., and Lavine, A. S., *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, Inc., Jefferson City, (2011).

[6] Cumpsty, N., and Heyes, A., *Jet Propulsion A Simple Guide to the Aerodynamics and Thermodynamic Design and Performance of Jet Engines*, Cambridge University Press, New York, (2015).

[7] Flack, R. D., *Fundamentals of Jet Propulsion with Applications*, Cambridge University Press, New York, (2005) DOI 10.1017/CBO9780511807138.

[8] DeMonbrun, M., Finelli, C. J., Prince, M., Borrego, M., Shekhar, P., Henderson, C., and Waters, C., "Creating an Instrument to Measure Student Response to Instructional Practices," *J. Eng. Educ.*, Vol. 106 No. 2 (2017), pp. 273–298. DOI 10.1002/jee.20162.