Methane-Oxygen Rotating Detonation Engine Exhaust Property Comparison

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Abstract

The purpose of this project is to demonstrate the course objectives of handling and analyzing large datasets using Python libraries. The data chosen for this purpose is calculated values of pressure, temperature, and normalized column density for carbon monoxide (CO) from the exhaust of a rotating detonation engine (RDE) while under operation. The data sets are representative of 4 separate runs of the RDE under varying equivalence ratios and mass flow rates. The author of this project has hypothesized that there is a correlation between the amount of CO generated and these two quantities and that correlation is detectable within the given data. Though a basic analysis of the data was conducted and some of the properties evaluated compared to those available from the original team's analysis, no correlation between the equivalence ratio, mass flow rate, and column density for CO could be determined.

Introduction:

Laser spectroscopy data was taken from a series of experiments conducted at the Air Force Research Laboratory's (AFRL) Rotating Detonation Engine (RDE) facility.[1] The objective of this project was to utilize this data to establish a relationship between the carbon monoxide column density, equivalence ratio (ratio of the actual fuel-oxidizer mixture, and the stoichiometric ratio), and combined mass flow rate of the fuel and oxidizer.

Pandas was used to organize the data quickly and make rudimentary comparisons such as correlations, dataset size, and to determine the basic structure of the datasets. NumPy was the primary mathematical tool used while conducting these analyses. Matplotlib was used to create graphs and visually inspect the original data, in addition to creating subplots of the processed data. Two modules were imported from SciPy library: "norm" was used for the determination of the distribution for the data and "find_peaks" was imported in an attempt to evaluate the peaks of the normalized column density data.

Data Scope:

The data collected has been processed from photodetector voltage signals being triggered by the light from a quantum cascade laser that has passed through the exhaust gases of an RDE while operating. The raw data is available; however, the original team worked for several months to develop the processing code for said data.[2] As such, it would be outside the scope of this project to scrub and process the raw data accordingly by generating an original code. The processed data consists of temperature, pressure, and normalized carbon dioxide column density for each test, taken at 250 or 500 million samples per second for 1.0 and 0.5 second test durations, respectively. The mass flow rate and equivalence ratio are constant parameters for each test and, thereby, are not a part of the collected data. All necessary information for test setup and methodology have been prepared in the referenced works. The data was chosen from the selected tests due to their relatively wide variance in the mass flow rate and equivalence ratio.

Each dataset required extensive comparison within each test series to determine linearity regarding sample index. The nature of a RDE is such that a detonation wave passes the sensor at a minimum frequency of 13.5 kHz. As such, there are several cycles worth of data within each test that will need to be averaged, compared, and analyzed. The data sets will be incorporated and isolated as separate data frames using the Pandas python library to make accessing separate time windows easier. Plotting of the data using the Matplotlib library in Python will be necessary for the purposes of visualizing the comparisons. Furthermore, it is proposed that a python software suite called Cantera be used to create a numerically simulated solution of the test data for comparison.[3]

The data's original format was that of .mat files. Each property from each run was in its own file and required compiling and organization.

Method:

The data originally came in .mat files which required conversion to .csv files to import and generate Pandas data frames. This was conducted in MATLAB, as it is a simple and effective process. After importing the required modules, libraries, and applications, the .csv files were read by Pandas and placed into a data frame for each run. The data obtained from the previous work cited, [1], are from runs 1, 5, 9, and 11, found in Table 1.

Table 1. Experimental Data and Test Matrix.[1]

Table 1
Summary of the LAS, high-speed camera, and CTAP measurements. Camera data was not successfully collected for test 25. Note: in all misaligned injector runs, wave modes were not sustained for the entire test duration with the sporadic creation and destruction of waves. Where multiple waves are indicated for the misaligned injector runs, smaller counter-propagating waves were present in addition to a dominant wave.

Test no.	ϕ	$\dot{m}_{tot}$ [kg/s]	CTAP [atm]	Cycle frequency [kHz]	Wave speed [km/s]	No. of waves	LAS record length [s]	Thrust [N]	Specific impulse [s]
Aligned injector									
1	1.09	0.277	4.1	16.8	1.88	2	1.0	387	143
2	1.18	0.268	4.0	16.7	1.87	2	1.0	378	143
3	1.29	0.268	4.0	16.4	1.83	2	1.0	374	144
4	1.40	0.268	4.0	16.3	1.82	2	1.0	378	143
5	0.77	0.268	3.6	15.4	1.72	2	0.5	334	126
6	0.95	0.272	3.9	16.8	1.88	2	0.5	360	136
7	1.04	0.091	1.4	14.0	1.56	2	0.5	62	70
8	1.05	0.177	2.6	16.2	1.81	2	0.5	200	114
9	1.02	0.363	5.3	16.4	1.83	2	1.0	543	151
10	1.06	0.449	6.1	22.1	1.65	3	0.5	690	167
11	1.51	0.091	1.5	13.5	1.51	2	0.5	71	77
12	1.42	0.177	2.7	15.5	1.73	2	0.5	209	120
13	1.44	0.354	5.1	16.5	1.84	2	1.0	543	157
14	1.39	0.445	6.3	21.0	1.56	3	0.5	734	168

This identification scheme was maintained throughout the process for the experiments and the properties (i.e. the data frames were named run1, run5, etc., with properties Pressure1, Temperature1, and so on). The data was further cataloged into data frames of their respective properties (i.e., there is one data frame for all the pressures, one for all temperatures, etc.). Once these steps were completed, a quick inspection of the data frames was conducted to ensure there were no issues with the data transformations. The data sets were not all equal length, indicating that the compiled property sets were populated with "NaN" where the smaller sets had no data to fill in place of the larger sets' indices. The property data frames were reduced in size by removing any rows with a missing value.

Following these procedures, both sets of data frames were evaluated for shape, maximums were compared across the property values, and a correlation was administered to each. No relevant information was determined from these simple checks. The data for each test was then plotted to determine a rough idea of the form. Figure 1 shows the plots of Run 1, Pressure, in its entirety and with a look at a much smaller sampling field.

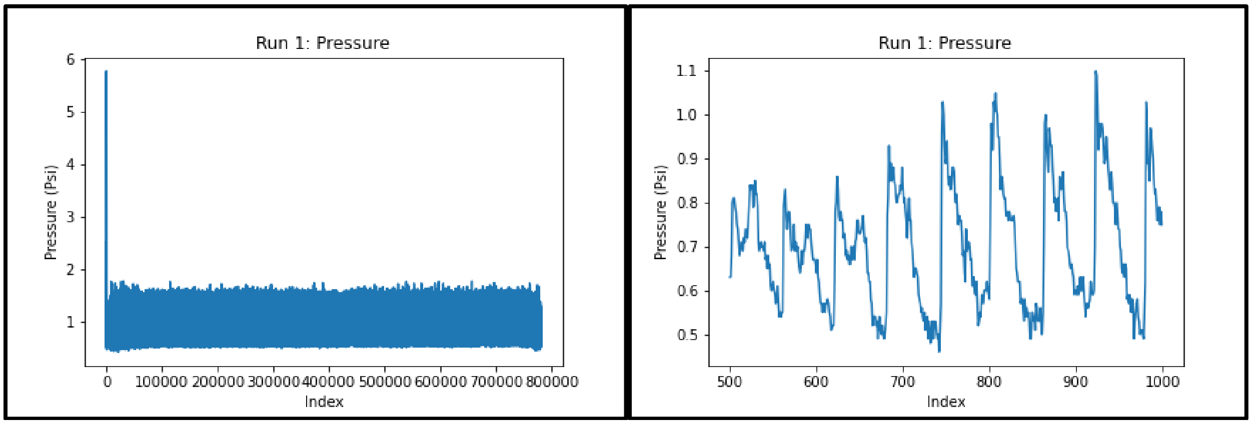

Figure 1. Plot of full (left) and reduced (right) span of Run 1, Pressure.

A correlation of the property data was conducted to determine the linearity between their indices. It was determined that a lag would have to be identified to make a proper comparison. The data are not synced in time as each test has a different initial point and frequency of occurrence. Attempts were made to determine the lag to make a proper correlation analysis, but no connection could be evaluated. Figure 2 shows the same index series from each of the pressure sets overlayed on one another. It is clear to see that none of the data are in synced in any significant way.

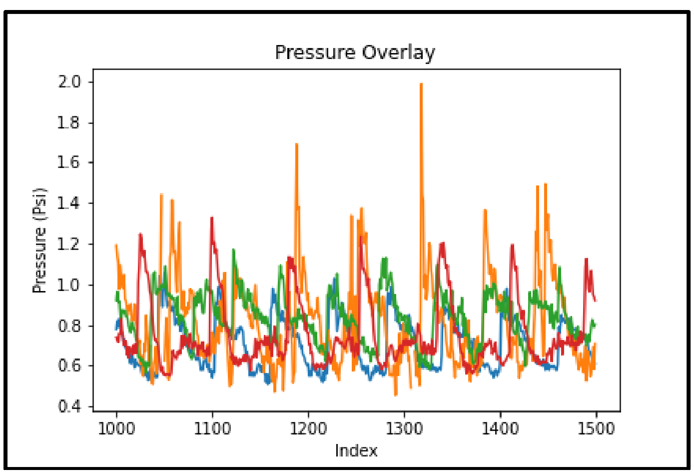

Figure 2. Overlay of Pressure Data from all Tests.

Given the sinusoidal nature of the original signals, a Fourier Transform analysis was conducted to determine the nature of the frequencies. In doing so, the frequencies of oscillation for the detonation waves within the anulus of the RDE were verified against the data in the referenced work. The frequencies of occurrence for each of the test series is determined from this analysis to be 16.8 kHz, 15.3 kHz, 17.1 kHz, and 13.7 kHz, for Runs 1, 5, 9, and 11, respectively. This, in turn, results in an overall percent error of 0.0, 0.6, 4.2, and 1.5.

Following these efforts several attempts were made to capture the peak values of the dataset. None were successful, however. Ultimately, it was the intent of the author to compile said data, determine its validity through a normal distribution curve, and compare each test's overall average against their respective mass flow rates and equivalence ratio in a 3D plot.

Conclusion and Future Work:

Overall, the methodology of the author to confirm the hypothesis should have been sound. However, given their lack of knowledge and experience, the goal was not met within the timeline given. Although, there will be a continued effort to complete this analysis in its entirety. To include overcoming the lack of correlation between the runs, and the compiling of each test's peak values for validation of the original hypothesis.

References:

[1] A. P. Nair, C. Jelloian, D. S. Morrow, F. A. Bendana, D. I. Pineda, and R. M. Spearrin, "MHz mid-infrared laser absorption sensor for carbon monoxide and temperature behind detonation waves," in AIAA Scitech 2020 Forum, 2020, no. January.

[2] A. P. Nair et al., "MHz Laser Absorption Spectroscopy via Diplexed RF Modulation for Pressure, Temperature, and Species in Rotating Detonation Rocket Flows," Appl. Phys. B, vol. 126, no. 8, p. 138, Aug. 2020.

[3] B. Franzelli, J. Rocchi, P. Wolf, A. G. Coriolis, and T. Cedex, "Cantera tutorial-V2.1," pp. 1–55, 2010.