Development of Highly Efficient Solid Oxide Fuel Cell (SOFC) Tail Gas Engine

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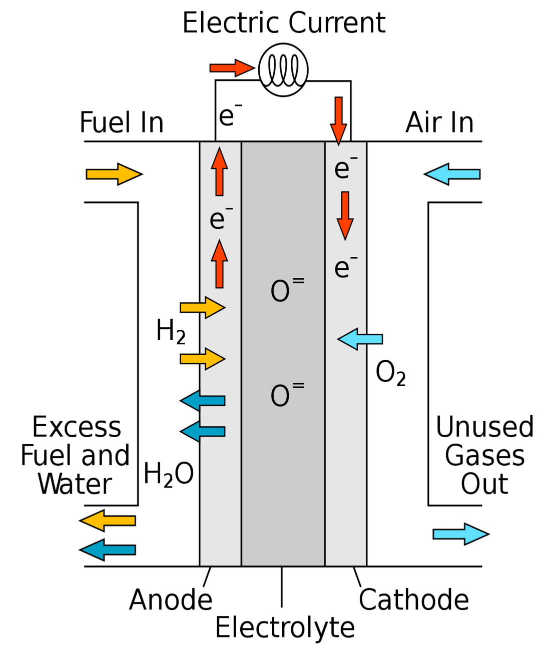
Motivation/Background

- There is a large increasing demand for electricity throughout the World.
- Microgrid energy distribution systems provide higher efficiencies and better stability compared to the current macrogrid system throughout the United States.
- Increasing the efficiency of fossil fuel-based electricity generation and distribution systems can reduce the cost of electricity and reduce greenhouse gas emissions.
  - These gas emissions are the inherent issues with traditional combustion-based power plants.
- Solid Oxide Fuel Cells (SOFC) offer a great alternative to traditional gas turbine microgrid electricity generation but are relatively more expensive.
- The anode tail gas (ATG) coming out of the fuel cell still contains energy-rich gases that can be used to power an internal combustion (IC) engine
  - The engine would be used to drive compressors to increase the energy density flowing through the SOFC further increase the efficiency of the system and reducing cost.

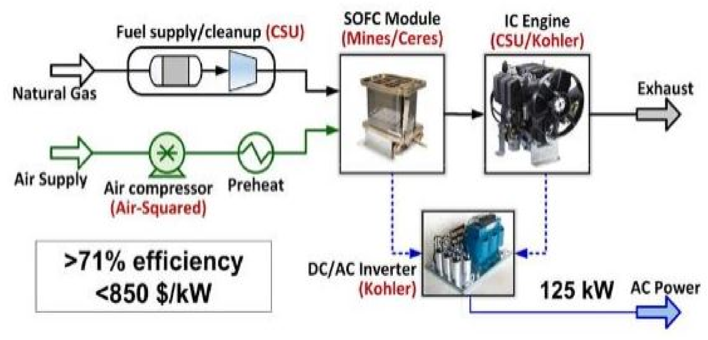


Solid Oxide Fuel Cell Schematic.

Solid oxide fuel cell. (2020, July 24)., from https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell

Anode tail gas composition.

	Molar Percentage				
	H2	CO	CH4	H2O	CO2
Anode Tail Gas out of SOFC	17.7%	4.90%	0.40%	48.7%	28.3%
Anode Tail Gas after Water Dropout	33.64%	9.31%	0.76%	2.5%	53.79%

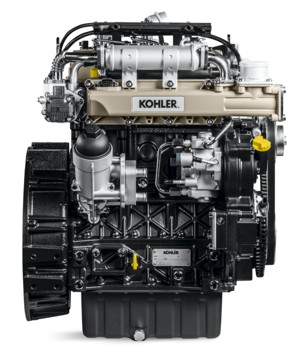


Overall System Schematic.

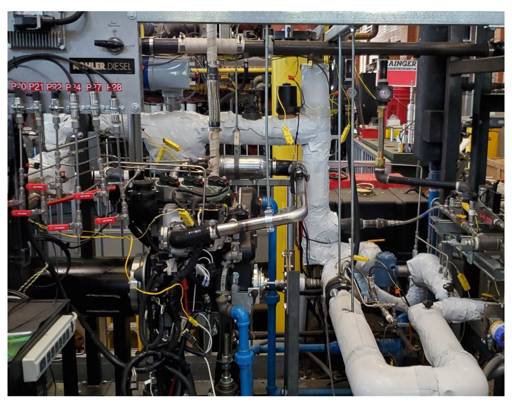
- The ATG has a very low energy density compared to other common fuels used in IC engines.
  - ATG lower heating value = 3.5MJ/kg
  - Natural gas lower heating value = 45MJ/kg.
  - The high hydrogen content of the ATG increases flame speed allowing for use in IC engine.
- Previous research has shown a SOFC + IC engine system is more efficient and lowers the cost of electricity compared to a SOFC by itself.
- Previous research for this project has shown a 1-liter spark-ignited engine can run on the tail gas, but challenges still exist in achieving power requirements, likely requiring the use of a larger engine.

Objectives

- The goal of this project is to develop a spark ignited IC engine that can run on the ATG and produce 15kW with a 35% thermal efficiency.
  - These targets for engine performance will put system efficiency above 70%.
- Identify optimum engine size.
  - Kohler 1-liter engine.
  - Kohler 2-liter engine.
- Optimize engine configuration/performance.



Kohler KDI1903 (2-liter)

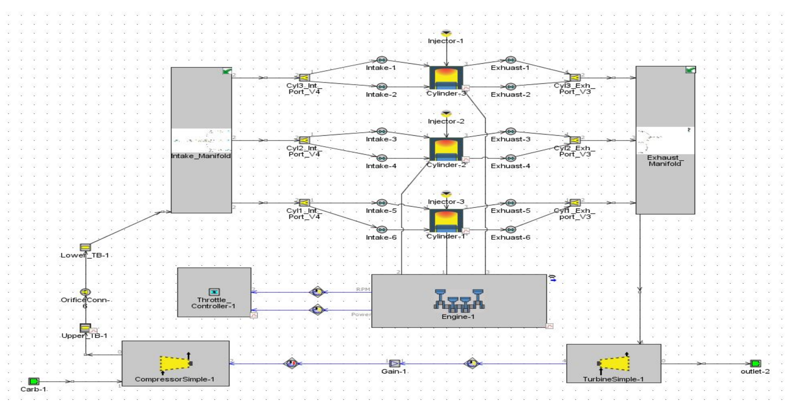


Current gasified 1-liter engine test cell.

Methods

GT-Power Software

- IC engine modeling software with high accuracy.
- Used to model stock Kohler diesel engines.
  - Verify models with engine test data.
- When the diesel engine models are accurate, they are then gasified.
  - Diesel injector replaced with spark source and ATG is added to the intake system as fuel.
  - The engine is then optimized to increase performance and efficiency.



GT-Power Engine Modeling Software Interface

Current 1-Liter Engine Testing

- Engine was modeled: verified, gasified, and optimized by previous graduate student.
- Test cell was created to test gasified engine.
  - Testing is showing unexpected backfiring limiting engine performance.
- Backfiring has led to the investigation into port fuel injection.
  - Eliminates the fuel propagating backfire through intake.
  - Can be used for 1-liter and 2-liter engine platforms.
  - Injectors were sized based off the mass flow rate of fuel needed and the following equation for flow through an orifice.

$$q_m = C\,A_2\,\sqrt{2\,\rho_1\,p_1\left(\frac{\gamma}{\gamma-1}\right)\left[(p_2/p_1)^{2/\gamma}-(p_2/p_1)^{(\gamma+1)/\gamma}\right]}$$

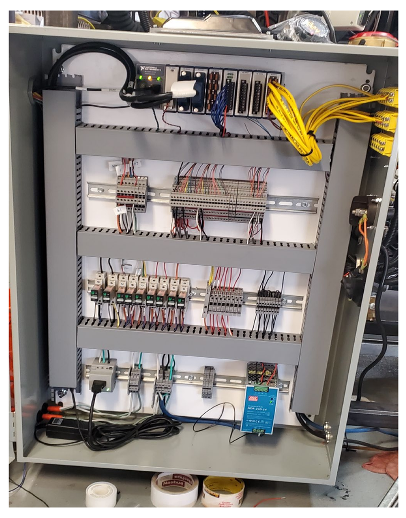
Methods Continued

2-Liter Engine Development

- KDI 1903 M engine was chosen to first be evaluated.
  - This engine is the naturally aspirated version of the 2-liter Kohler diesel engine.
  - Easier to model and a simpler engine design with less parts to fail.
- Information from the workshop manual was used to define the model.
  - This includes specific geometric dimensions to define the combustion chamber such as:
    - bore, valve diameter, valve location, and injector location.
  - Also includes other geometric dimensions to help define engine friction:
    - Stroke, connecting rod length, number and dimensions of main crack bearings, and valve train configuration.

Kohler KDI1903M

KDI 1903 TCR Engine Test Cell



- The performance curves in the workshop manual were then used to verify the model.
  - The efficiency and fuel injected were calculated from the fuel specific consumption curve.
  - Fuel injected per cycle was imported into GT-Power allowing for the model to run.
  - The brake torque, power curves, and calculated efficiency was compared to the GT-Power results.
  - Need more engine test data to more accurately verify model, but Covid has made it difficult to receive any test data from Kohler.

2-liter Engine Test Cell

- KDI 1903 TCR engine was chosen to be explored after results from KDI 1903 M engine.
  - Turbocharged version of the 2-liter Kohler diesel engine.
  - A more accurate model was wanted by being verified with engine test data, so an engine test cell was developed.
- Piping and instrumentation diagrams and bill of materials was created for test cell.
- Test cell was constructed.
- Control/wiring box was developed to control the engine and record all engine test data.

Results

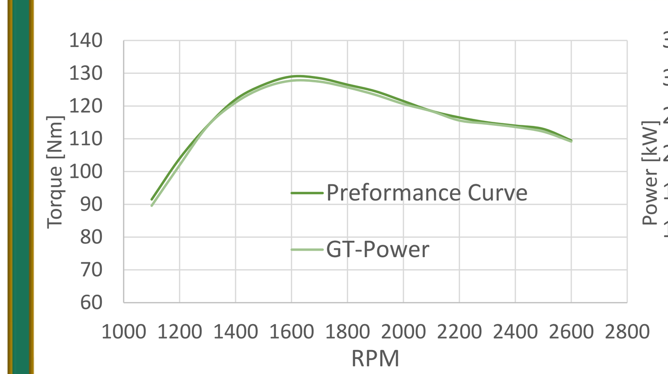
1-Liter Engine

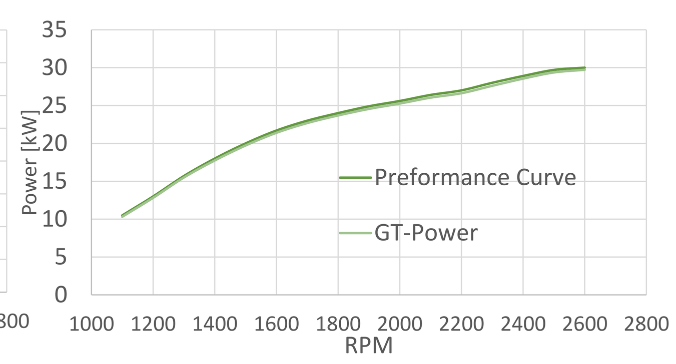
- Up to 12kW of power and 32% efficiency, but:
  - Constant backfire which is most likely caused by high intake pressure, temperature, and sharp combustion chamber corners that have high temperatures.
  - Turbocharger not correctly sized, using electronic supercharger to increase intake pressure. The engine is relatively small and there is not a correctly sized turbocharger for engine.
  - Long ignition delay with abnormal heat release in cylinder during combustion. Most likely caused by unsymmetric/abnormal combustion chamber geometry, especially location of spark plug.
- IMPCO Es2 natural gas injectors were selected for port injection of the ATG.

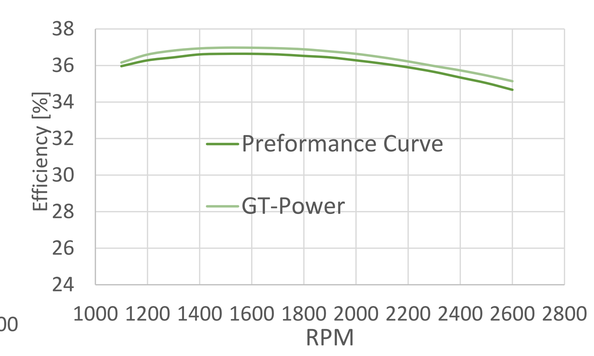
2-Liter KDI 1903 M Engine

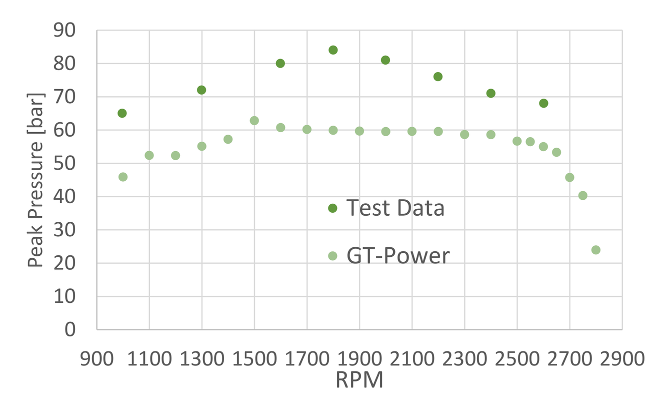
- GT-Power results of simple diesel model were compared to manual performance curves.

KDI 1903 M Diesel Model Verifying Results





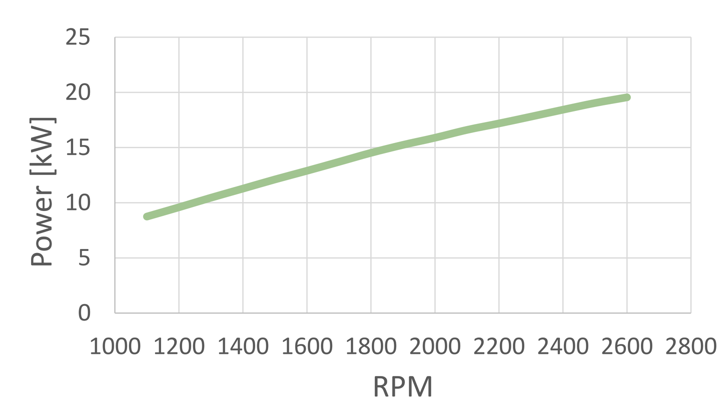




- GT-Power results were accurate compared to the performance curves (top 3 graphs) but was not accurate for in cylinder pressure compared to some engine test data received from Kohler (left graph).
  - Showed we need to install in-cylinder pressure transducer to record combustion data to make more accurate model.
- Showing promising results, the model was gasified and optimized.

Gasified KDI 1903 M Results

- GT-Power results of gasified KDI 1903 M showed project brake power output requirement was not met until 1900RPM and max power was only 20kW.
  - Desired lower RPM to decrease fatigue and increase engine life.
  - Decided to use the turbo charged version of KDI 1903 engine, KDI 1903 TCR, to increase power output at lower RPM. Led to development of test cell.



Conclusion and Future Work

- 2-Liter engine offers more advantages over the 1-liter.
  - Already matched turbocharger and more options for correctly sized turbocharger.
  - More symmetric shape combustion chamber, allowing for centrally located spark plug for optimized combustion.
  - Larger size allows lower RPM, thus decreasing fatigue and increasing engine life.
- Modeling results showed the need to use the turbocharged version of the 2-liter engine.
  - Need to collect test data from engine to make accurate model before gasifying = test cell development.
- The chosen fuel injectors need to be installed on the 1-liter and testing needs to be preformed to see if engine performance can be improved.
- An in-cylinder pressure transducer needs to be installed in the 2-liter diesel and testing needs to be completed to collect data to verify model.
- The 2-liter diesel model will then be gasified and optimized to see engine performance when powered by ATG, which then can be compared to the 1-liter.