PROGRESS REPORT

PROJECT TITLE: <u>Efficient Range Extender Using E85 and Thermochemical Recuperation</u>
PROJECT NUMBER: 1097-19EU
PROJECT PERIOD: April 2019-March 2022
REPORTING PERIOD: Oct-2021-December 2021
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1.) PROJECT ACTIVITIES COMPLETED DURING THE REPORTING PERIOD. (*Describe project progress specific to goals, objectives, and deliverables identified in the project workplan.*)

The overall objective of this project is to develop a high efficiency range extender (REx) engine generator using E85 as a fuel. The project will allow development of key understanding regarding ethanol/gasoline blend steam reforming chemical kinetics. The fundamental understanding will then be applied by constructing a practical TCR reactor. The reactor will be constructed for application in a BMW engine already installed and operational at the University of Minnesota TE Murphy Engine Research Laboratory (MERL). The project will lead to demonstration that E85 can improve the efficiency of TCR-equipped REx engine-generators and provide a more renewable alternative to lower concentration blends, adding to the environmental benefits of electrification. The objectives relevant to this reporting period are as follows:

- Determine electrical efficiency improvements with catalytic reactor installed on BMW engine using ethanol/gasoline fuel blends – months 12-18 (revised months 24-30)
- Revise reactor as needed and disseminate findings through conference presentations, journal publications, and discussions with OEMs – months 30-36

<u>Progress Update:</u>
During the reporting quarter, the BMW engine encountered some mechanical issues that prevented experiments from being completed. Preliminary results from experiments completed show that the aftertreatment catalyst provided sufficient heat to steam reform splash blended E85. Work is ongoing to determine improvements in efficiency and emissions from the engine using the reformed fuel blend. Additionally, modeling work is underway to better understand mult-cylinder efficiency improvements using the TCR system. The final report will include all experimental data and modeling work proving a quantitative engine efficiency gain.

2.) IDENTIFY ANY SIGNIFICANT FINDINGS AND RESULTS OF THE PROJECT TO DATE.

During the first half year of the project, modeling was conducted using the engine simulation software GT-Power. The engine configuration shown in the figure below was considered in the study. The engine was operated experimentally at a selection of speed and load conditions show in the table.
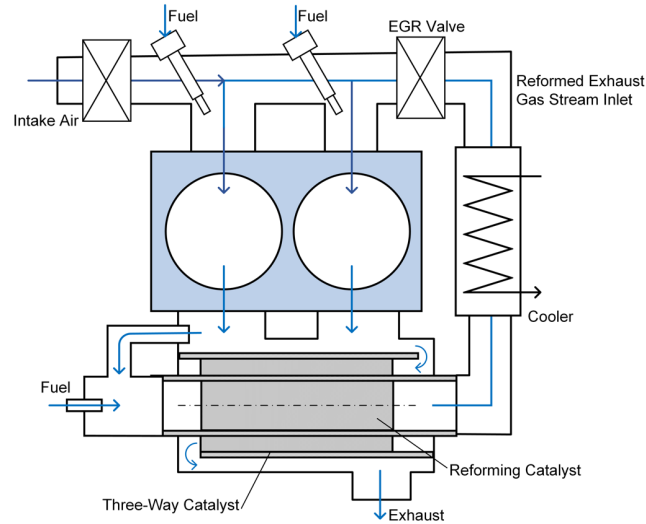

Figure 1: System examined in simulation study of thermochemical recuperation in REx engines.

Table 1: Selection of speed and load points considered for the study

Case	Speed (rpm)	Electric Power (kW)
1	2700	11.1
2	3000	5.1
3	3000	10.7
4	3300	13.5
5	3300	11.8

A model of the 2-cylinder BMW REx engine was built in the GT-Power 1-D simulation environment. It was comprised primarily of an engine model and an integrated aftertreatment model. The engine model used intake and exhaust and cylinder geometry measured from the test engine located at the UMN MERL. The model without the TCR reactor was run using the default combustion model provided in GT-Power. This baseline model did incorporate the close-coupled TWC that is used in the vehicle and provided with the REx engine. Throttle valve open percentage and backpressure were tuned for each of the conditions given in Table 1 at the given engine speeds to achieve the same brake output power as was found in the experiments. Brake power output from the experiments was calculated assuming 90% generator efficiency.

The engine was operated with a stoichiometric air to fuel ratio for all the modeling and experiments. This mixture was maintained by controlling the oxygen concentration in the exhaust manifold to a constant value determined from experimental measurements. The engine fuel to air ratio was not specified in the model due to the need to account for gaseous fuel contained in the reformed EGR stream. Therefore, a controller was inserted into the model to

control fuel injected to match a desired exhaust O_2 concentration. The fuel used in the modeling was pure iso-octane though non-oxygenated pump gasoline (90 RON) was used in the experimental work. The engine combustion model for all simulations was a Wiebe Function with an assumed a constant combustion phasing of 50% mass fraction burned crank angle (CA50) of 7.0 degrees after top dead center. The combustion duration did not change with fuel type and the combustion efficiency was maintained at 97%.

A conceptual diagram of the counter-flow TCR model is shown in Figure 2. In the model, the exhaust gas and EGR stream are in a counter-flow configuration. Each catalyst section was assumed to consist of a 100 cells per square inch monolith substrate. The three-way catalyst was assumed to have a total volume of 2.0 liters and the reforming catalyst had a volume of 1.0 liters. Heat was transferred between sections by assuming a conductive metal path between them. The baseline chemical kinetic model for the TWC reactor provided in a template in GT-Power was used. Limited literature exists describing the kinetics of gasoline steam reforming. Literature provided steam reforming kinetics for iso-octane over nickel catalysts were used for the reforming section.
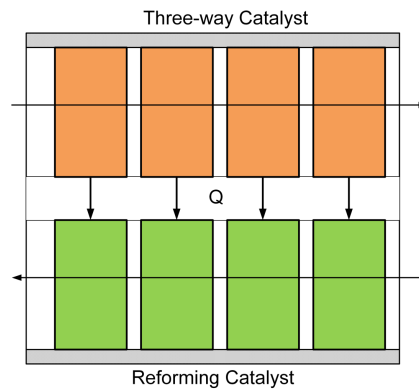

Figure 2. Conceptual model of thermochemical recuperator used in the modeling

The model was validated using experimental data collected from the REx engine installed in the laboratory. Modeling results with the TCR reactor were analyzed as follows:

The integrated model was run holding the throttle position and engine speed constant. Therefore, the BMEP of the engine dropped as the exhaust gas recirculation (EGR) percentage increased. With increasing EGR percentage, the percentage of fuel sent to the reformer section versus the engine increased because the molar steam to carbon ratio (S/C) was held constant at 1.0. All plots shown in this section depict performance over the range of EGR run in the parametric study from 0-32%.

While the BMEP decreased by 1.4 bar with increasing EGR, the BSFC improved by 2.9% through the use of the TCR reactor. The manifold inlet pressure also increased by 4 kPa (not shown) over the EGR range. To increase engine load for higher EGR rates, enough pressure difference must exist between the exhaust and intake manifold, which will ultimately restrict the maximum load for a TCR equipped engine. However, for REx engines, the engine need not operate at WOT since there is no vehicle acceleration requirement. Therefore, an engine could be designed to operate with sufficient pressure differential to drive EGR at one peak efficiency point.
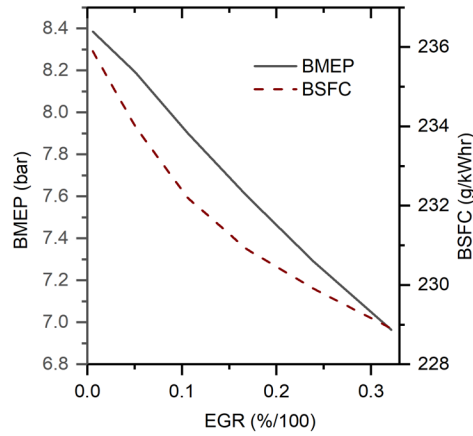
Figure 3: BMEP and BSFC of the engine versus EGR percentage.

Figure 4 shows the overall performance of the reforming reactor at the chosen operating point. The fuel fraction sent to the reformer over the total fuel sent to the engine and reformer increased from zero with no EGR to up to approximately 50% at the highest EGR point. However, the fuel conversion through the reformer, defined as the percentage of fuel converted to H_2 and CO also decreased with increasing EGR due to insufficient residence time in the catalyst. The peak gas hourly space velocity based on standard conditions (298 K and 101 kPa) at the highest EGR rate was 10,556 hr^{-1}. For the Ni-based SR catalyst described in [19], such a short residence time is only capable of converting about 22% of the fuel. If a larger reforming catalyst is used, or one with precious metal active materials, as was used in our previous experimental work for hydrous ethanol [17], it is expected that even greater conversion could be achieved at higher EGR rates. The energy ratio, defined as the lower heating value of reforming products to that of the reactants into the reactor was highest with the highest conversion. Therefore, if the conversion could be increased at higher EGR rates, the energy ratio would increase and the engine BSFC could be further improved. More experimental data from actual reforming reactors are necessary to determine SR kinetics at engine relevant conditions and with appropriate substrates before true efficiency improvement potential of the TCR reactor can be predicted.
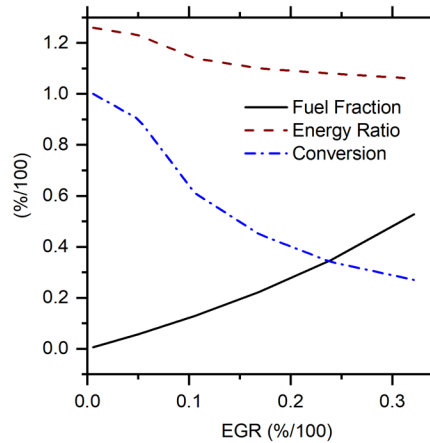

Figure 4. Reformer fuel fraction, reformer total energy ratio, and reformer catalyst conversion efficiency as a function of EGR.

The TCR reactor operates by converting both sensible heat from the exhaust with chemical energy from the TWC oxidation reactions to increase SR reaction conversion efficiency. The 2.9% decrease in BSFC of the engine shown in Figure 3 is a result of heating value improvement of the reformed fuel (i.e.; positive energy ratio) in proportion to the quantity of fuel reformed. Therefore, even though the energy ratio was the highest for low EGR, the amount of fuel reformed was near zero, so the net fuel efficiency benefits were lower. However, although the energy ratio for high EGR was only slightly above one, over 50% of the fuel to the engine, times 25% conversion, or 12.5% of the total fuel was converted to products with higher energy content.

In the second part of the project, a TCR reactor was designed and developed as shown in Figure 5. This reactor will be integrated with a BMW engine at the University of Minnesota MERL. The reactor has been designed to operate with one cylinder of the multi-cylinder engine to isolate the effects of the reformed ethanol on engine combustion. The TCR reactor includes two catalyst modules as shown in the figure that include outer and inner reactor sections. The ethanol and EGR mixture flows through the center portion of the catalyst and the exhaust flows through the outer annulus. Modeling and experimental work has been completed to validate the heat exchange effectiveness of the catalyst modules and will be included in an upcoming publication on the topic.
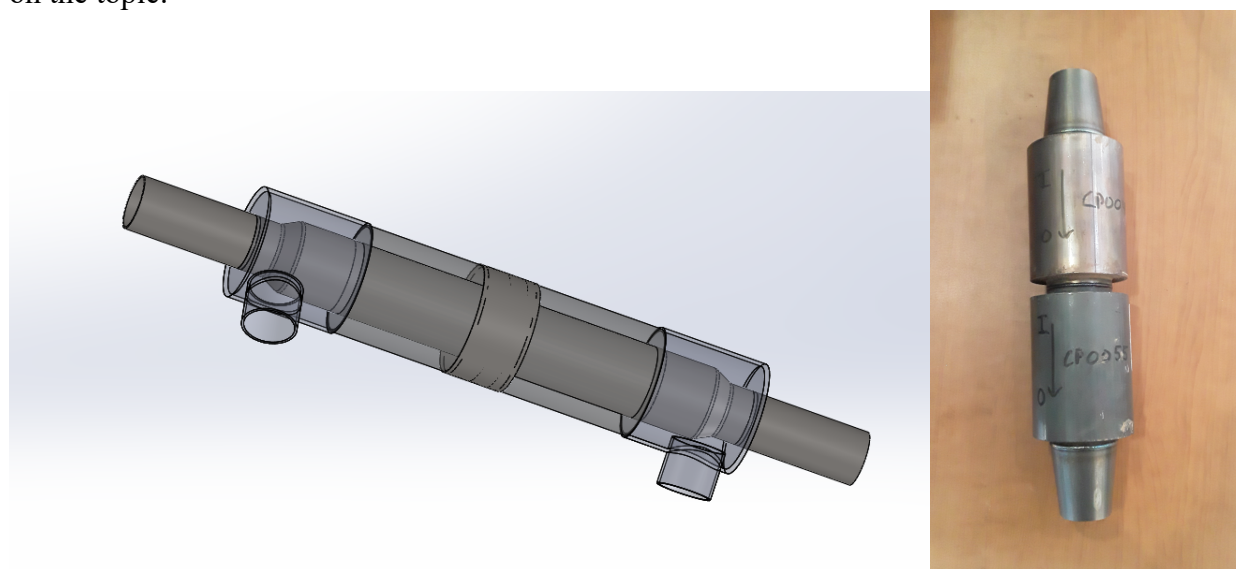

Figure 5. CAD model of the single module reactor design to be integrated with the BMW test engine in the second part of the project (left), and actual catalyst modules welded and ready for integration in the reactor (as of 8/1/2021) (right).

The reactor was completed in August of 2021 and was integrated with the BMW engine at the MERL as shown Figure 6 below. Testing of the unit will commence in November of 2021 and will be completed by the end of the project period. Testing will be conducted using one cylinder of the BMW engine to isolate the effects of cylinder to cylinder variations.
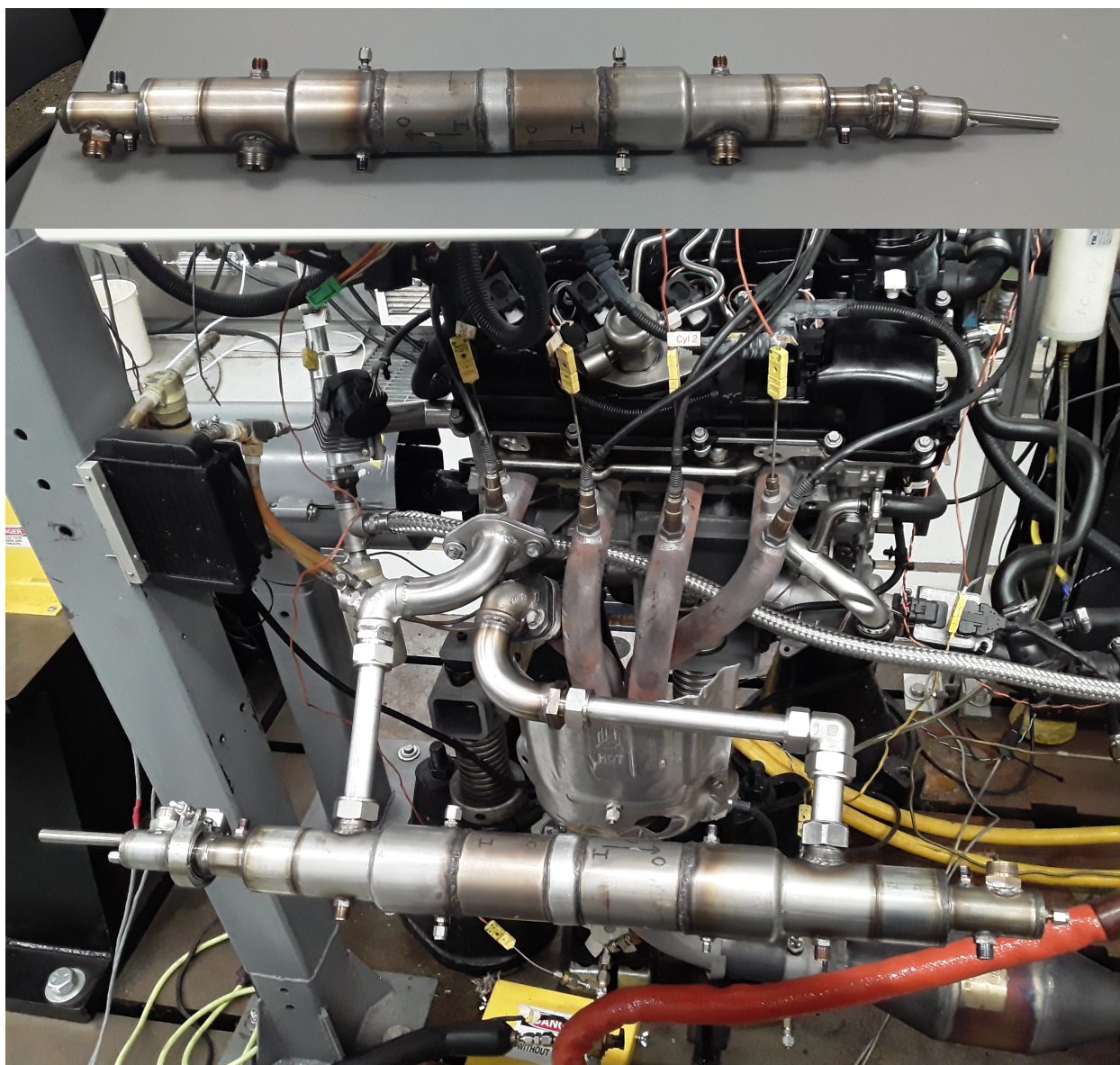
Figure 6. (top) Completed reactor ready for testing, (bottom) reactor mounted in one cylinder of BMW engine ready for experiments

3.) CHALLENGES ENCOUNTERED. (*Describe any challenges that you encountered related to project progress specific to goals, objectives, and deliverables identified in the project workplan.*)

As previously mentioned, the COVID-19 pandemic restricted work on the project significantly due to laboratory restrictions. Further challenges encountered included sourcing the catalysts needed for the reactor depicted in Figures 5 and 6. The catalyst supplier, Johnson Matthey LLC underwent significant restructuring such that they could not supply the coated modules for over one year. The reactor was finally delivered and assembled in October of 2021 and is installed for testing.

Additional challenges included the control of the BMW REx engine located at the UMN MERL. To simplify the project, a BMW engine will be tested with the reactor on only one cylinder to

isolate the effects of the reformed ethanol blends on the engine operation. The experimental results will be analyzed to determine the effect that the developed system would have if implemented on a full multi-cylinder engine in a vehicle. It is expected that such analysis will be included in the final project report.

4.) FINANCIAL INFORMATION (*Describe any budget challenges and provide specific reasons for deviations from the projected project spending.*)

No budget challenges were encountered during this period.

5.) EDUCATION AND OUTREACH ACTIVITES. *(Describe any conferences, workshops, field days, etc attended, number of contacts at each event, and/or publications developed to disseminate project results.)*

The results of the modeling portion of the project were presented at the SAE IC Engines 2019 conference on Sept. 16-19, 2019 and was accepted as a journal paper by SAE. The paper is available upon request. An additional publication has been prepared on the TCR reactor and will be submitted to the International Journal of Hydrogen Energy in early 2022.