Diagnostic Instruments for Advanced Efficiency Automotive Systems

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Technology Summary

Researchers at Oak Ridge National Laboratory (ORNL), in collaboration with a major engine manufacturer, have developed a suite of instruments for advanced internal-combustion-engine (ICE) efficiency, durability, and control.

To meet increasingly strict worldwide fuel economy (efficiency) requirements and emissions standards, automotive manufacturers will need to dramatically improve ICE performance and durability and further reduce emissions in the coming years. This will require greater knowledge of what is going on inside engines and exhaust systems, specifically performance variations from cylinder to cylinder and cycle to cycle. Existing measurement tools and techniques have insufficient temporal and spatial resolution and limited access to many relevant ICE locations; i.e., they lack the crank-angle and intra-cycle temporal resolution necessary to characterize and identify origins of cylinder- and cycle-specific performance variations. The vibrations, temperatures, condensates, and particulates associated with engine applications are harsh and complicate measurements. The ORNL suite of tools meets the needs for robust, cost-effective, advanced diagnostics that can operate in harsh environments to accelerate development of low-cost, clean, fuel-efficient, durable engines and related automotive systems.

The ORNL instrument offers a broadly configurable diagnostic system for enabling better engine-system development and requires minimal modification to base engine hardware for simultaneous spatial and temporal mapping of O_2, CO_2, H_2O, temperature, and pressure. The instrument contains multiple optical sources and detectors, and different probes, described below, can be tailored to accommodate specific customer applications. Robust optical-fiber coupling between the instrument and probes contains the light and provides for flexibility and safety.

- **Optical Backscatter Probe.** The optical backscatter probe enables rapid measurement of particulates at typically inaccessible or hard-to-reach locations in engine systems. Fast (crank-angle resolved) measurements allow the backscatter probe to evaluate particulate variations from individual cylinders. The 1/4 in. outside diameter (OD) probe is easy to apply and requires only a single access boss, and multiple probes can be applied for simultaneous measurements at multiple locations throughout the engine.

- **EGR Probe.** Exhaust gas recirculation (EGR) is a technology used to reduce NO_x ($NO + NO_2$; oxides of nitrogen) emissions and involves mixing exhaust with the intake air charge. Spatial and temporal nonuniformities in the EGR-air mixture can cause cylinder-to-cylinder and cycle-to-cycle combustion variations, degrading engine efficiency and performance. The EGR probe simultaneous measures CO_2 and H_2O concentration, temperature, and pressure from four separate probes with 5 kHz crank-angle resolution; the measurements are based on laser-absorption spectroscopy, and other species including CO and CH_4 are possible. The 3/8 in. OD probes mount via single-port access bosses, require minimal modification to base engine hardware, allow monitoring at difficult-to-reach engine locations, and can be individually translated for spatial mapping of parameter distributions in the intake and exhaust. The probes are robust to particulate depositions and can be continuously operated for over 4 hours in diesel- and gasoline-engine applications; when needed, probe cleaning takes only minutes using a pipe cleaner and can be performed without stopping the engine. Using CO_2 and/or H_2O as an EGR marker, the EGR probe allows spatial and temporal mapping of EGR uniformity and variations. The EGR probe detects cylinder- and cycle-specific combustion variations via corresponding variations in the exhaust, intake-EGR and combustion-residual backflow into intake runners. In relatively constant-temperature applications such as the intake manifold, a lower-cost LED EGR probe, which uses a light-emitting diode (LED), is possible.

- **Transient Exhaust Measurement Apparatus (TEMA).** The TEMA is an instrumented duct that adds transient O_2 concentration to the suite of measured gas parameters and can be conveniently mounted at various exhaust or intake points throughout the engine system via standard exhaust flanges. It provides 5 kHz crank-angle-resolved measurements of spatially average O_2 concentration across the TEMA duct and is intended for applications where spatial resolution is not required; the apparatus allows for path-averaged CO_2 and H_2O concentration, temperature, and pressure, and other species are possible. The TEMA uses the same instrument as the EGR and optical backscatter probes, and any combination of the probes and apparatus can be implemented for parallel measurements using the various diagnostic system technologies within this suite.

Advantages

- Resolves fast performance fluctuations in:
  - – CO_2, H_2O, O_2, temperature, and pressure
  - – EGR
  - – Particulate
  - – Combustion
- Crank-angle (5 kHz) temporal resolution detects cycle-to-cycle and cylinder-to-cylinder variations
- Allows spatial mapping of EGR-mixing uniformity
- Analysis method allows simple and reliable applications
  - – Analysis based on fundamental absorption theory and fixed probe optical pathlength
  - – Spectroscopic knowledge not required for operation
  - – Routine calibrations not required
  - – Analysis is robust to particulate deposits and vibrations
- Faster than commonly used development tools including FTIR (Fourier Transform Infra-Red) and NDIR (Non-Dispersive Infra-Red)
- Easy and minimally invasive probe access
  - – Single access boss requires minimal modification of base hardware
  - – Broad access throughout engine, including typically hard-to-access locations
  - – TEMA uses conventional exhaust flanges
- Probe design is robust and simple to use
  - – Robust to typical engine vibrations, temperatures, and particulate
  - – 4+ hr of continuous operation demonstrated in diesel and gasoline engine applications
  - – Fast cleaning without stopping engine
  - – Simple probe translation for spatial mapping via non-swaging ferrule and nut
- Fast, on-the-fly analysis
  - – Real-time feedback
  - – Incorporation into standard engine-cell data-acquisition systems
  - – Assessment and implementation of advanced control strategies
  - – Characterize temporal instabilities
- Simultaneous measurement from multiple probes
  - – Any combination of EGR, optical backscatter, and TEMA probes
  - – More extensive system assessment

Potential Applications

- EGR-intake and overall engine-system design
- Assessing and reducing combustion variations
- Critically assessing and tuning engine-design models
- Implementing and evaluating control strategies
- On-road and PEMS (portable emissions measurement systems) studies
- Next-generation engine-efficiency advances
- Faster technology development and implementation

Patents

James E. Parks and William P. Partridge. *Optical Backscatter Probe for Sensing Particulate in a Combustion Gas Stream,* US Patent 8,451,444 B2, issued May 28, 2013.

James E. Parks, II; William P. Partridge, Jr.; and Ji Hyung Yoo. *EGR Distribution and Fluctuation Probe Based on CO_2 Measurements,* US Patent 9,000,374 B2, issued April 7, 2015.

James E. Parks, II; William P. Partridge, Jr.; and Ji Hyung Yoo. *EGR Distribution and Fluctuation Probe Based on CO_2 Measurements,* US Patent 9,068,933 B2, issued June 30, 2015.

William P. Partridge, Jr.; Gurneesh Singh Jatana; Ji-Hyung Yoo; and James E. Parks, II. *Diagnostic System for Measuring Temperature, Pressure, CO_2 Concentration and H_2O Concentration in a Fluid Stream,* US Patent Application 15/355,762, filed November 18, 2016.

William P. Partridge, Jr.; Gurneesh Singh Jatana; Ji-Hyung Yoo; and James E. Parks, II. *Diagnostic System for Measuring Temperature, Pressure, CO_2 Concentration and H_2O Concentration in a Fluid Stream,* US Patent 9,541,498 B1, issued January 10, 2017.

William P. Partridge, Jr., and Gurneesh S. Jatana. *Transient Exhaust Measurement Apparatus,* US Patent Application 62/454,935, filed February 6, 2017.

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