TECHNOLOGY STATUS ASSESSMENT
(Revised)

Prepared by

Gary D. Bourn

SwRI Project No. 03.10198
DOE Contract No. DE-FC26-03NT41859

Prepared for

U. S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

November 24, 2003

SOUTHWEST RESEARCH INSTITUTE®

SAN ANTONIO
HOUSTON
WASHINGTON, DC

SOUTHWEST RESEARCH INSTITUTE
6220 Culebra Road
San Antonio, Texas 78238

TECHNOLOGY STATUS ASSESSMENT

Prepared by

Gary D. Bourn

SwRI Project No. 03.10198
DOE Contract No. DE-FC26-03NT41859

Prepared for

U. S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

November 24, 2003

Approved:

signature on original
James J. Cole, Acting Director
Design and Development Department

TABLE OF CONTENTS

I. INTRODUCTION

This document provides a technology status assessment for "Advanced Compressor Engine Controls to Enhance Operation, Reliability, and Integrity." SwRI is conducting this project for DOE in conjunction with Cooper Energy Services, under DOE contract number DE-FC26-03NT41859. This report addresses the current status of engine controls for integral compressor engines and how the technology to be developed in this project compares.

II. INTEGRAL COMPRESSOR ENGINES

The gas transmission industry operates over 4,000 integral engine compressors, the majority being two-stroke, with a median age of 50 years and a median size of 2000 horsepower. These engines pump at least half of the 23 TCF of natural gas presently consumed in the United States. These engines are no longer produced, and with the projections for future increased demand of natural gas and the expense of replacement, it would be advantageous to modernize the existing fleet to allow for continued operation with increased efficiency and emissions compliance.

These engines are unique in that the compressor is integrated into the engine design, and is therefore not a separate component. A cross-sectional view of a typical integral compressor engine is provided in Figure A-1. The compressors are reciprocating units, mostly double acting, with *pockets* to change the individual clearance volumes and, in-turn, the throughput of the individual compressors. The reciprocating design of the compressors creates an uneven loading of the engine within each revolution, and the sequence in which the pockets are open or closed (load steps) creates an additional variance in the dynamic loading. Since the compressors are connected directly to the crankshaft, and a variable dynamic load is induced, the instantaneous rotational velocity (IRV) of the crankshaft is affected. Add in the fact that combustion is never completely stable, the IRV is further exacerbated.

The dynamically variable IRV is important for the two-stroke engines due to the fact these engines are port scavenged, and the actual time duration of port opening for a given cylinder is a function of the IRV in that particular phase of the cycle. Variable port open duration between cylinders will affect the scavenging and trapped mass of air in each, causing different trapped air/fuel ratios. A difference in trapped air/fuel ratios between cylinders will in-turn affect the engine-out, or average, efficiency and emissions.

An additional aspect of integral compressor engines, especially the two-stroke designs, is that they feature direct in-cylinder fuel admission (injection) to prevent scavenging of raw fuel into the exhaust. This direct fuel admission was originally performed with a cam-actuated poppet valve that has a fixed duration tied to crankshaft speed. The control variables with this design are the main fuel header pressure and individual *pinch* valves to each cylinder that are manually adjustable. A governor typically modulates the main fuel header pressure to maintain the engine speed setpoint. The pinch valves are manually adjusted to provide some compensation to individual cylinders to balance combustion.

III. COMPRESSOR ENGINE CONTROLS

The current state of engine controls in the population of integral compressor engines is widely varied. Many of these engines still feature the original mechanical and/or pneumatic control devices that are decades old in their design. Another fairly large segment of the population has somewhat more advanced controls that feature electronic controllers (i.e. PLC). These are referred to below as Global Engine Electronic Controls. There are also a few engines that feature recently developed control systems incorporating electronic fuel injection. The electronic fuel injection systems have been mostly installed on units in non-attainment areas of which none of the less advanced systems can help these units meet the emissions standards.

A. Mechanical/Pneumatic Control Systems

The original design engine control systems were mainly speed governing systems with manual controls for periodically setting engine balance, spark timing, and air manifold pressure (AMP) if turbocharged. The goal of the original integral engine designs was to move gas through the pipeline network. There was no concern for exhaust emissions at the time of their design, and fuel efficiency was less of concern as that cost was recuperated in the sell of the gas. Reliability and durability were of main concern. Increased capacity was addressed by designs of larger engines with either larger compressor cylinders or more compressors per unit.

As mentioned previously, speed governing was accomplished with a mechanical governor that modulated the main fuel header pressure, which in-turn changed the fuel flow rate. The main fuel header connects the gas admission valve (or fuel injection valve) in each cylinder, much like an intake manifold connects to the inlet ports of each cylinder. The gas admission valves are cam-actuated poppet valves that allow fuel to flow directly into the cylinder, much like an intake valve on a four-stroke engine allows air to flow into the cylinder. Therefore, the main fuel control valve that is controlled by the governor, is similar in function to a throttle on the intake tract of a four-stroke engine. There are also manually adjusted pinch valves installed between the main fuel gas header and each gas admission valve to allow for balancing the flow to each cylinder. These components can be seen in Figure A-1.

The design of this basic fuel system is very simple and leaves much room for improvement with current technology. The only feedback to this system is engine speed and the only cylinder-to-cylinder optimization that can be done is from manual adjustment. Balancing of each cylinder was, and still most commonly, based on the mean peak firing pressure measured from each cylinder at a given engine operating condition. Obviously, this process cannot be dynamic and therefore cannot compensate quickly to changing conditions of speed setpoint, load step, fuel quality, ambient conditions, and many other factors.

An example of one such setup is a Clark HBA-6T that was tested as part of DOE project DE-FC26-02NT41646. On this in-line six-cylinder turbocharged engine, the AMP was set manually by adjusting a regulator in the panel to change the air pressure to a pneumatic actuator on the wastegate. The ignition timing was set via a manually adjusted trim pot in the ignition module. When this engine was first tested, the combustion stability was very poor as quantified by the spread in peak firing pressures between cylinders and between cycles. The AMP was set relatively high, causing a lean air/fuel ratio, and the ignition timing was set six degrees retarded from OEM specifications. The response to questions on why these settings were utilized was that the engine would experience detonation (knock) during hot ambient temperatures. Thus, the lack of automatic controls with feedback led to the manual adjustment to a condition where the engine would operate safely under most conditions, but far from optimal at any one condition.

B. Global Engine Electronic Controls

The intermediate step in compressor engine control state-of-the-art is a system utilizing electronic control units to control the global engine functions. Global controls imply that only overall engine systems are controlled, with no automatic individual cylinder optimization. There a few levels of control sophistication in this category, although each level still relies on use of the original cam-actuated gas admission valves and pinch valves.

The basic level involves automatic control of AMP through wastegate adjustment. Typically, a relationship of AMP versus main fuel gas header pressure is derived from empirical data on a particular unit. This function is programmed into the controller and the AMP is automatically adjusted based on the fuel gas header pressure feedback signal. Often, coefficients for the function vary with engine speed. This strategy is often termed 'air/fuel ratio control' [1]. However, the lack of known discharge or flow coefficients, prevent an accurate airflow determination and true control of air/fuel ratio to a precise setting.

Additional control features to improve the control strategy include spark timing adjustment, governing algorithms, safety warnings, and automatic startup/shutdown procedures. The spark timing adjustment feature typically involves either the electronic control module interfacing with the ignition control module or a more advanced ignition module acting independently. With either approach, the spark timing is adjusted as a function of engine speed, AMP, or both. Speed governing can be performed by the engine control module if an electronic control valve is installed in the main fuel gas header. With electronic governing, algorithms can be programmed to more intelligently and more quickly control the engine speed.

More advanced levels of this category of engine controls include two-way communication with the ignition module and additional sensor inputs for more sophisticated engine controls. One technique that was recently published involved use of additional measurement signals and a simple airflow model to estimate the required AMP for a given air fuel ratio target [2]. A tuning process was required with this method to empirically determine coefficients for an engine speed correction function.

The most advanced level of this control strategy includes the use of a fairly complex engine model programmed into the control module. With the sensor data and some empirical derived (or approximated) coefficients, the model predicts the NO_X emissions and adjustment of the AMP is performed to achieve a set level [3]. The NO_X prediction models are termed Parametric Emissions Monitoring (PEM). Some techniques include a predicted trapping efficiency and fuel/air equivalence ratio for which the AMP setting is derived [4].

The most sophisticated levels of this type of control category perform significantly better than the original mechanical/pneumatic systems. Emissions levels can be maintained fairly well and compensation for differing operating or ambient conditions is included to a fairly significant degree. The difficulty with these systems is the need for engine mapping or tuning to determine the various coefficients, constants, and model parameters. These systems are also far from the level of modern controls available on today's automobiles due to the lack of full authority control of the fuel admission and other functions, and precise fuel/air equivalence ratio measurement.

C. Electronic Fuel Injection

The more modern control systems on integral compressor engines are ones that include recently developed electronic fuel injectors. The electronic fuel injectors are similar to the mechanical gas admission valves due to the continued use of poppet valves. The differences include the actuation of the poppet valve and installation of shrouds or nozzle caps to better direct the fuel jets for improved mixing. The supply pressure is also significantly increased over the mechanical gas admission valves for further improvements in in-cylinder fuel/air mixing. There are three actuation techniques employed by these available designs, and include the following.

1. Electro-hydraulic
2. Electro-pneumatic
3. Electro-magnetic

The flexibility provided by electronic injection includes the ability to vary injection timing and duration. The speed governing is performed with pulse-width modulation of the injection duration, and the fuel gas header pressure is maintained constant. Very fast control of engine speed is available with these injectors. The improved mixing due to the injection valve shrouds/nozzle caps and pressure creates improved combustion rate and stability. The improved combustion allows for leaner operation and, therefore, reduced NO_X emissions [5]. Thus, the systems are becoming popular for retro-fit of units in non-attainment areas.

The control strategy is often similar to the advanced techniques described in the previous section. An increased level of control is incorporated with the addition of dynamic cylinder pressure sensors for semi-automatic compensation for cylinder-to-cylinder differences. This is often termed "auto-balancing" and the use of mean values for cylinder peak firing pressures are used for compensation of individual cylinder fueling. The electronic injection provides the capability required to automatically bias the cylinder-to-cylinder fueling to balance the mean peak firing pressures.

A recent research project demonstrated the coupling of individual cylinder timing control with an electronic injection system described above [6]. In this project, the cylinder pressure data was used to bias the ignition timing to individual cylinders for balancing the location of peak firing pressure. This effort was accomplished with an experimental control system that communicated with a modern ignition module to accomplish the ignition biasing. This strategy coupled with the individual injection duration biasing adds a further degree of control sophistication for further improvements in performance and emissions. It was this project that identified the potential affect on individual cylinder airflow from IRV and compressor load step.

D. Advanced Control Strategies

The subject research project will further add to the state-of-the-art in compressor engine controls. The use of the combined NO_X/O_2 sensor will allow direct measurement of the exhaust NO_X emissions and fuel/air equivalence ratio, and eliminate the models or correlations that can only estimate these values. This will add tremendous flexibility for widely variable operating conditions on a given engine, and more easily adapt to different engine makes and models. In addition this project seeks to increase the control capability for individual cylinder optimization. Improved individual cylinder optimization will require some means for individual fueling control, as well as improved algorithms for determining the trapped fuel/air equivalence ratio. The goal is to add a further level of control sophistication to the best features of the above described systems for additional improvements in efficiency and emissions control.

IV. CONCLUSION

In conclusion, the state-of-the-art in compressor engine controls is improving steadily, but lacks in sophistication and performance relative to the levels being achieved in modern automobiles. There are differences in the engine designs and operation between compressor engines and automotive engines. However, there are many techniques and strategies that can be utilized in both, either directly or with modification. This project seeks to utilize advanced sensors, such as the NO_X/O_2 sensor and modern dynamic pressure transducers, to incorporate direct feedback of the main control parameters that affect equivalence ratio and NO_X emissions. Advanced algorithms for improving the emissions-efficiency trade-offs will also be developed in this project.

V. REFERENCES

1. Ely, Charles, “Air/Fuel Ratio,” Anderson Consulting, Training, & Testing publication, http://www.classactt.com/acttnow.htm.

2. Malicke, Dustin and Mathews, Hans, “Equivalence Ratio Based Air/Fuel Ratio Control Strategies,” Gas Machinery Conference, October, 6, 2003.

3. Kubesh, John and Liss, William, “Simple NO_X Model for Predictive Emissions Monitoring,” ASME Paper ICE-Vol. 21, 1994

4. Beshouri, Greg, “Designing Engine Retrofits for Emissions Reduction,” Gas Machinery Conference, October, 2002.

5. Huntley, Dean and Mathews, Hans, “Fuel Injection Reduces Emissions,” Pipeline and Gas Technology, January, 2003.

6. Smith, Jack, “Integration Of Engine And Compressor Controls”, SwRI Report to Gas Machinery Research Council, May, 2002.

Appendix A

Figures

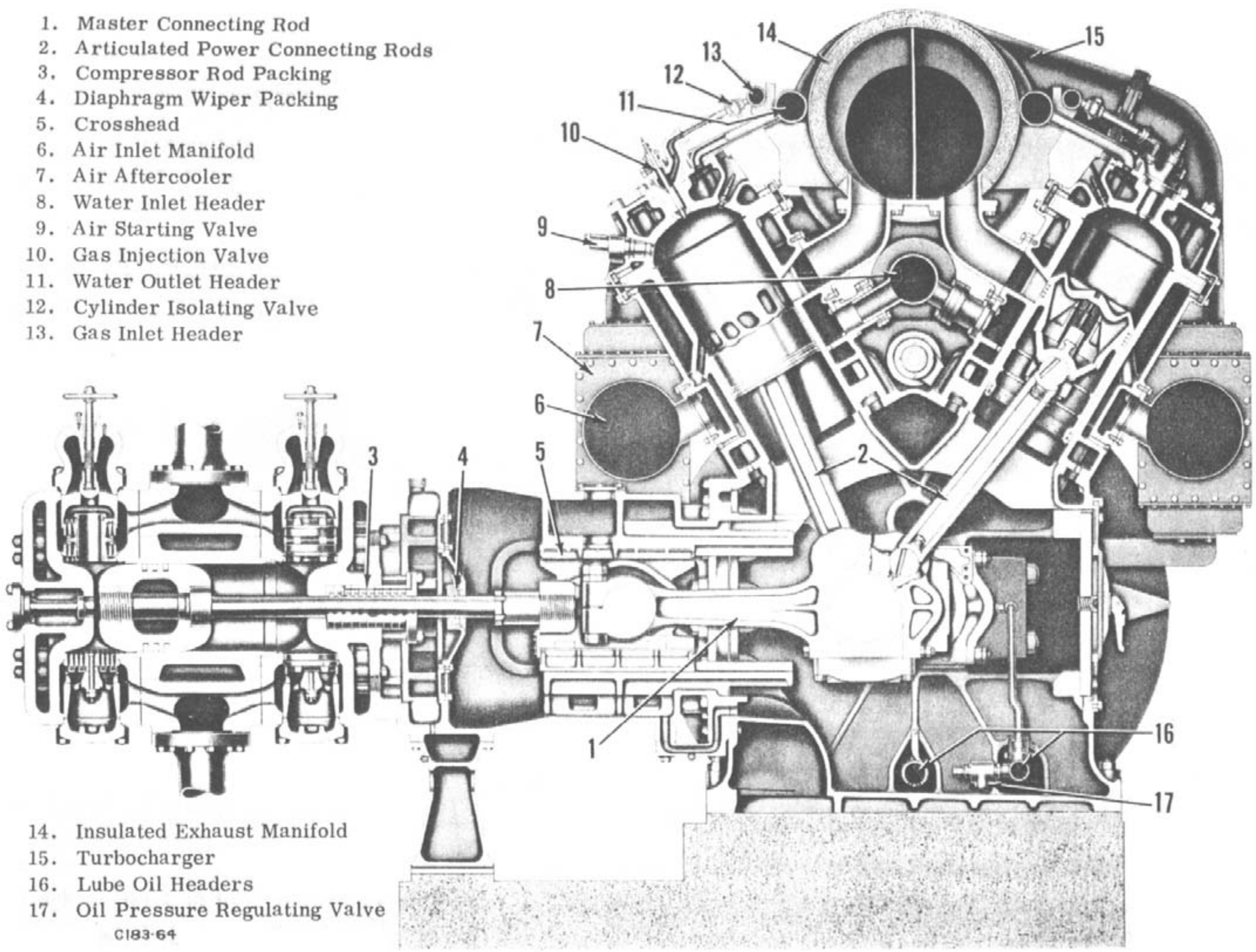

FIGURE A-1. Cross-Sectional View of Typical Integral Compressor Engine