

Figure 1: Cylinder Liner Schematic.

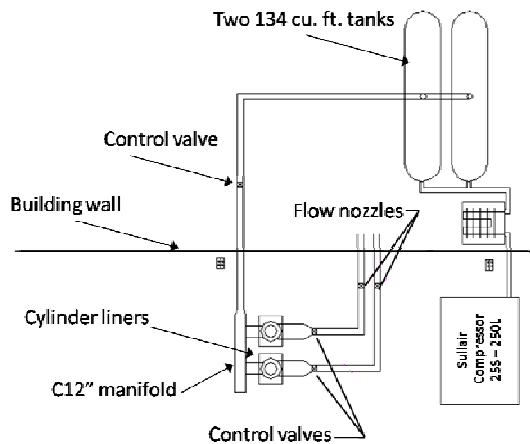


Figure 2: Test Cell Schematic.

each cylinder. A series of engineering computer models under development at K-State will provide the information necessary to quantify the impact of air flow imbalance. With this knowledge, the air flow to each cylinder can be modified to achieve a balance. A component of these models will allow engineers to analyze the air flow through the engine system before and after air flow correction.

The models will be validated using air flow data collected on the expanded Air Flow Test Bench (AFTB) that, once completed, will include multiple cylinders. Figure 1 schematically shows two overhauled GMV power cylinders positioned on the test cell. The liners, donated by El Paso Corporation, were refurbished and shipped by Arrow Industries of Jena, Louisiana, all of which was time and effort donated to the project. The two-cylinder AFTB will have the capacity to independently measure the air flow into and out of each cylinder as well as the capability to individually control each cylinder.

Active Air Control

NGML researchers are investigating technology developments to mitigate the problem of non-balanced power production from the cylinders, as well as non-balanced NO_x production from each cylinder. This project falls under the Pipeline Research Council International, Inc. Emissions Reduction for Legacy Engines roadmap.

Current philosophies on balancing engine cylinders rely on manipulating the fuel flow rate to individual engine cylinders. Most methods manipulate the fuel flow rate to balance either the peak in-cylinder pressure or the ratio of peak cylinder pressure to cold compression pressure. These methods inherently assume the trapped mass (not including fuel), and the trapped fresh air is the same for each cylinder. This typically is not the case. As a result, current balancing practices can, and do, create imbalanced equivalence ratios between the cylinders. This trapped equivalence ratio imbalance results in non-balanced NO_x production from each cylinder. In the worst case, some cylinders operate too lean for stable combustion, some operate lean with stable combustion, and the remaining operate fuel rich (although still to the lean side of stoichiometric) and produce disproportionately high quantities of NO_x.

The challenge to achieve balanced air delivery to multiple cylinders rests with the physics of the intake and exhaust manifolds. The manifolds as designed impede equal air distribution from the turbocharger to

Figure 2 shows the layout of the two-cylinder AFTB that has been designed as a component based system to allow for easy transition between flow testing projects. This flexibility provides the industry a low-cost opportunity to use the test cell to test retrofit designs and/or monitoring technologies.



Figure 1: Low Flow Test Cell Volume Bottles.



Figure 1: Low Flow Test Cell Compressor Site.



Figure 1: Low Flow Test Cell Burner Site.

Low Flow Test Cell

Engineer designers of off-road diesel engines, such as those used in agriculture, construction and mining, are challenged to meet tight NO_x and particulate matter emissions requirements that are being phased-in between 2008 and 2014 based on engine size and power output. To meet these levels, a close integration will be required between the turbocharger/engine, controls, and the after treatment technology.

To help meet a growing need for fine-tuned turbocharger designs needed to meet a wide variety of operating conditions, the NGML is building a low flow turbocharger test cell. “We have had numerous requests over the last 18 months from various turbocharger designers and test facilities to provide independent testing services,” said Kirby Chapman, NGML director. “Given our expertise with large turbocharger testing and performance analyses this expansion into the low flow market dovetails well with our current operations,” he said.

The Low Flow Test Cell (LFTC) will provide flows up to 1,500 scfm at 120 psia. The turbocharger inlet piping is fitted with a low NO_x burner to allow for full air temperature control up to 1,500°F. The LFTC also will be equipped with a fully computerized data acquisition system to insure data collection integrity. The test cell, housed in a climate controlled, sound proof test chamber, has the capability for containment, endurance and performance tests.

As with any NGML project, undergraduate and graduate engineering students are heavily involved with the design and construction. From pouring concrete to programming the data acquisition system, students have completed nearly all of the work. Additional students will be hired to help run the test cell once it is fully commissioned, which is scheduled for late 2007. The hands-on application to their coursework has consistently made K-State engineers with NGML experience valuable employees to the energy industry.



Figure 1: BP and NGML Instrument Waukesha 330 VRG.



Figure 1: Emissions Sample Line Leading to the Stack.



Figure 1: Emissions Sample Line Leading to the Enclosed Testo Emissions Analyzer.

NSCR Characterization of Gathering Engines

As part of a US DOE-funded project, NGML researchers have focused on applying emissions-lowering technologies originally developed for large-bore slow-speed reciprocating engines to their smaller cousins used in the oil and gas gathering industry.

The technology of choice for four-stroke cycle rich-burn engines has been the addition of a non-selective catalyst (NSCR) reduction system with an air-to-fuel ratio controller (AFRC) to maintain the correct chemical mix in the catalyst. However, the results from a 2006 South Coast Air Basin of California study have indicated that: 1) very low NO_x levels are not continuously achievable from NSCR systems, 2) transient behavior of AFRC/NSCR systems are poorly understood, and 3) catalyst solutions produce deleterious quantities of ammonia at low NO_x levels (McGivney, 2006; Arney, 2006). Furthermore, regulatory agencies, such as those in Colorado, New Mexico, and Wyoming, have started to focus on emissions from reciprocating engines below 50 bhp that until now have not been regulated.

With funding from a consortium of stakeholders, the NGML has partnered with Innovative Environmental Solutions to fully characterize non-selective catalyst reduction (NSCR) catalysts and air-to-fuel ratio controllers (AFRC) used on gathering engines. Three engines located in the Farmington, New Mexico area have been instrumented for semi-continuous emissions monitoring. These include a 68 hp Waukesha 330 VRG, 23 hp Compressco GasJack, and 1,100 hp Waukesha 7042. Three additional engines will be tested monthly. Expectations are that the monitoring will continue for one year to encompass all weather conditions. The measured and calculated parameters that will be used to assess NSCR/AFRC performance are brake specific fuel consumption, pressure and temperature changes across the catalyst, trapped equivalence ratio and lambda sensor output pre- and post-catalyst, and specific emission rates.

Objectives for this project are:

1. Identify the reliable capabilities of currently-available NSCR/AFRC solutions
2. Evaluate the effect of load/cyclical operation and fuel quality on NSCR/AFRC performance
3. Characterize emissions including NO_x, ammonia, and the NO_x/ammonia trade-off during the year-long study
4. Understand the AFRC limitations
5. Understand the physics and chemistry behind the transient response of the engine/NSCR/AFRC system relative to NO_x and CO formation, and the NO_x/ ammonia trade-off
6. Provide hardware/software/control technology recommendations that are necessary to reliably constrain NO_x, CO emissions, and the NO_x/ ammonia trade-off

Current financial contributors to the project are the American Petroleum Institute, the U.S. Department of Energy, BP of Americas, the Pipeline Research Council International and Enginuity LLC. Additionally, Compressco, EMIT Technologies, and Miratech contributed equipment to the project.

The implications of this study extend well beyond the Four Corners region where significant concerns about regional haze control have accelerated NO_x and fine particulate regulations that are only pending in many other producing areas. However, the incremental adoption of regulations state-by-state, as well as the proximity of remote production areas in the Southwest to National Parks and Class I Wilderness Area may likely stimulate aggressive compressor engine controls. Finally, the East Texas and Louisiana regions are subject to conventional ambient ozone concerns and have promulgated strict NO_x controls for reciprocating engines.

The second phase, for which funding has not yet been secured, is to use the collected data to validate physics- and chemistry-based models of the NSCR/AFRC system. Researchers will use these models to better understand the NO_x – ammonia tradeoff and improve AFRC algorithms. In addition, the NGML will install and test a Compressco GasJack compressor/engine, which is a predominant engine used in the oil and gas gathering industry. This test cell will allow researchers to fully explore field results in a laboratory setting, fine tune developed AFRC algorithms based upon modeling efforts, and test advanced sensors. Compressco of Oklahoma City Okla donated a new GasJack engine to the NGML in 2006 for this project.

Turbocharger Component Matching System

The NGML research team is completing development of a science-based methodology that will provide the ability to computationally mix and match various components used in turbochargers on large-bore reciprocating engines. Proper component specification will assure maximum overall turbocharger efficiency at the engine design operating point and will all minimize the need for costly field iterations. Furthermore, optimal turbocharger component selection will increase overall turbocharger performance and thereby lower engine backpressure. Lower engine backpressure improves engine breathing engine scavenging, and engine efficiency.

Thoroughly modeling a turbocharger at equilibrium conditions requires a complex set of mathematical equations that must be solved simultaneously. Fortunately, these mathematical equations are well-understood and are available in the public domain. The development focuses on:

1. The compressor impeller and casing;
2. The turbine nozzle ring and turbine blades;
3. The second law of thermodynamics losses that occur in each of these components;
4. Coupling the turbine and compressor; and
5. Energy losses to the cooling water system.

As an example, Figure 1 shows of the flow chart of the compressor model. The TuCMS program calculates velocities, pressures, temperatures, pressure reductions, and efficiencies throughout the compressor system using a specified set of geometries and atmospheric conditions. Losses in rotating parts are more pronounced and impact compressor performance much more than those in stationary components. Rather than combining the losses as a slip factor and/or loss coefficient, TuCMS individually accounts for losses that have the greatest impact on compressor performance.

Engineers can use the TuCMS program as a tool to conduct a preliminary performance analysis to match different turbocharger components before manufacturing and implementation of a given turbocharger build.

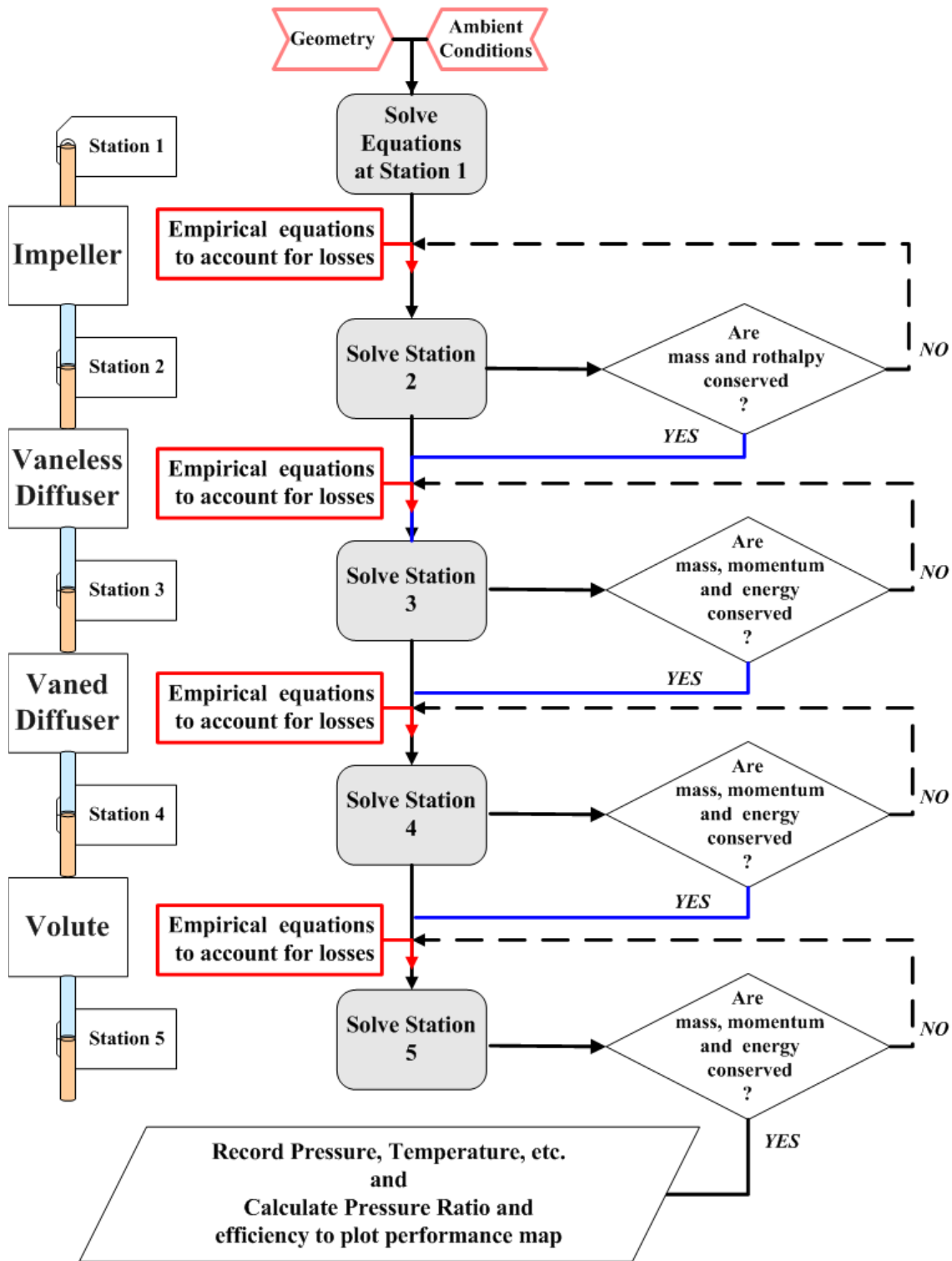


Figure 1: Compressor Modeling Technique Flow Diagram.



Figure 1: Ajax DP-115 Engine on the Test Stand.



Figure 2: Data Acquisition System in the Control Room.



Figure 3: Manifold and Tanks Used to Blend Fuel.

Natural Gas/Hydrogen Blend to Reduce Two Stroke Cycle Engine Emissions

With the recent ruling by the US Supreme Court confirming the EPA's authority to regulate greenhouse gases, engine researchers such as those at the NGML continue to identify methods to lower combustion temperatures while maintaining complete combustion.

Blending hydrogen into an engine's fuel can lower in-cylinder combustion temperatures and reduce pollutant emissions. Because hydrogen has a wider flammability range in comparison to natural gas the engine can be operated leaner and with lower combustion temperatures. Specifically, the very high molecular diffusivity of hydrogen creates a more uniform mixture of fuel and air. Hydrogen also has very low ignition energy, which translates into easier combustion.

NGML researchers tested hydrogen as a fuel additive on the Ajax DP-115 test cell. The engine is a large-bore, two-stroke-cycle, single-cylinder, natural-gas-fueled engine. The engine was first operated at the test point on pure natural gas and allowed to stabilize. Then a mixture of hydrogen and natural gas at various molar percentages was introduced. Engine and emissions data were recorded and physical observations were also noted, such as engine misfires.

Results showed that the addition of hydrogen into the fuel gas reduced emissions. A nominal 10% hydrogen concentration resulted in an almost 5% reduction in fuel consumption, as well as a 21% reduction in NO_x emissions. In addition, CO emission levels remained nearly constant with hydrogen addition. Implementing hydrogen addition in the field would likely involve generating it on-site.



Figure 1: Low Emissions Burner Installed on the NGML Turbocharger Test and Research Facility.



Figure 2: Gas Train in the Foreground Used to Fuel the Burner.

Development of a Turbocharger Booster System

Air flow through an engine provided by a turbocharger can be impeded by a couple of different conditions such as:

1. High air flow rates required to reduce NO_x emissions decrease the turbine inlet temperature. This equates to reduced available energy to drive the turbocharger turbine. The necessary power balance between the turbocharger turbine and compressor is then only achieved over a narrow engine operating range typically near full load and speed
2. During hot ambient conditions, the reduced air mass flow rates reduce the available energy at the turbine inlet. As a result an engine cannot operate at the designed trapped equivalence ratio above a certain ambient temperature.

To overcome these problems, NGML researchers designed and tested a Turbocharger Booster System (TuBS). The TuBS system consisted of relatively small dry low emissions burner installed between the exhaust manifold and the turbocharger turbine nozzle ring along with a gas train for fuel delivery, provisions to bleed a small amount of air from the compressor discharge piping for the burner, and a control system.

This system provided the means to increase the turbine inlet temperature and in turn increase the turbocharger rotation. The increased speed provided a higher air mass flow rate through the turbocharger compressor to the engine. Emissions did not appreciably increase as a result of the addition of a burner.

This project is part of the Pipeline Research Council International Emissions Reduction for Legacy Engines program that focuses on the development of cost-effective technologies and methodologies to achieve 0.5 grams NO_x/bhp-hr at full load and speed, and maintain the lb/hr emissions equivalent of this level throughout the full operating range for 80% of legacy pipeline engines currently in use.

Laboratory testing proved the proof-of-concept. The addition of a small booster system burner increased temperature at the turbine inlet and improve compressor side conditions without a significant increase in NO_x emissions. CO levels were affected by the burner.

Similar results are expected from installation on an engine, which will be implemented in 2008. Field installation will present its own unique challenges as researchers must design a system that is not only

practical and cost-effective to install but also safe and easy to maintain. With the addition of a burner, albeit small, permitting issues will have to be reviewed.