ESTABLISHMENT OF AN AIR COMPRESSOR EXPERIMENTATION FACILITY VIA UNDERGRADUATE STUDENT PROJECTS

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Abstract

The Mechanical Engineering Department at The University of Wisconsin-Milwaukee (UWM) has recently established an *Air Compressor Experimentation Facility* through several mechanical engineering undergraduate student projects. Initial funding for the lab was provided by a University of Wisconsin System Applied Research Grant and by a donation solicited from a local compressor company. The facility houses four industrial 15-hp rotary screw air compressors, a high-speed PC-data acquisition system (PC-DAS), highly-sensitive instrumentation (e.g., watt transducer, pressure transducers, relative humidity sensor, sound level sensor and temperature probes) and a state-of-the-art infrared imaging radiometer.

Several mechanical engineering students have worked on independent projects to establish this *Air Compressor Experimentation Facility*. These projects include (i) the design, setup and implementation of a PC-DAS with instrumentation to measure, monitor and record air compressor performance, (ii) the measurement of energy savings achievable by using advanced synthetic lubricants, (iii) the effect of environmental and operating conditions on air compressor performance, (iv) the thermal analysis of air compressor operation using a thermal imaging camera, (v) the creation of a procedure to independently test several lubricants in a single air compressor, and (vi) the development of a web page containing information learned in the laboratory.

This paper presents the student projects that developed this test facility, preliminary experimental results generated by these student projects, and the educational experiences of our undergraduate students who worked on the projects.

Introduction

In 1997, the authors received a University of Wisconsin System Applied Research Grant to establish the *Energy Conversion Efficiency Laboratory* in the Mechanical Engineering Department at The University of Wisconsin-Milwaukee. The initial funding was supplemented by the donation of four Atlas Copco Model GA11 15-HP rotary screw air compressors, many filters and various air compressor lubricants from a local air compressor company. Subsequently, four undergraduate students were employed to work on independent projects to develop this experimentation facility so that measurements of air compressor performance and energy efficiency data could be obtained. Two of these students used this experience to assist them in finding jobs after graduation, one of the students has chosen to remain working on the project as a graduate Research Assistant, and the fourth student continues to work as an undergraduate Project Assistant in this lab and in another research laboratory.

In this paper, the authors (who were the students' supervisors) describe the projects that the students worked on and present the preliminary experimental results obtained in the laboratory. In addition, the educational experiences of these mechanical engineering undergraduates are outlined.

Student Projects

The tasks of the undergraduate students working in this experimentation facility were divided into the six distinct projects described below.

Project 1: Instrumentation Setup and Implementation[1]

The first undergraduate student project involved the development of the basic laboratory layout, and the initial setup and implementation of the PC-data acquisition system (PC-DAS). The primary issues involved in this project were the design of the overall laboratory to allow for the installation and operation of four industrial-sized air compressors, and the initial setup of the sensors for monitoring the environmental conditions in the laboratory and the operating parameters of the air compressors (Figure 1). Each air compressor was approximately 450 kg and had dimensions of 102 cm x 79 cm x 117 cm (L x W x H).

Figure 1. *Air Compressor Experimentation Facility.*

The primary issues to be addressed by the student in the design of the laboratory layout were the management of the air exiting the compressors, and the development of a suitable back-pressure or load on the air compressors. These problems existed because there was little demand for the compressed air in the building, and a suitable storage tank for the air was unavailable. It was determined that the most effective way to vent the air was to assemble a piping system to direct the discharge air into an existing ventilation duct which led to the roof of the building and exhausted to the environment. To mimic realistic operating conditions, an orifice plate in the exhaust line of the air compressor was found to be a sufficient method for providing a back-pressure on the air compressors. Two orifice plates were designed, fabricated and installed for testing (Figure 2). The first orifice plate contained a 0.476 cm diameter hole and was found to produce highly-unsteady operation of the air compressor. This resulted in frequent loading and unloading of the system which did not represent typical air compressor operation. To overcome this problem, a second orifice plate with a 0.595 cm diameter hole was created and installed. By allowing for a greater flow of air through the system, this orifice plate was found to produce a much smoother operation of the compressors (more consistent load) and corresponded better with actual operating conditions. An added benefit of this smoother operation is that data analysis was greatly simplified because of the static nature of the power consumption.

Figure 2. Two orifice plates employed by students to provide a load to the air compressor system (orifice plate on right is orifice plate design 2).

Once the air compressors were installed and operating in a industrial-like fashion, it was necessary to instrument the equipment so that environmental and operating conditions could be monitored. The parameters of concern were the ambient air temperature, the discharge air temperature, the barometric air pressure, the discharge air pressure, the relative humidity of the supply air, and the temperature and pressure of the lubricant. To start, the student tapped into an existing pressure sensor in the air compressors to measure the exiting air pressure (P_{exit}). Moreover, Type-T thermocouple probes were calibrated and installed to measure temperatures, a barometric pressure transducer was employed to measure the changes in barometric pressure, and a relative humidity sensor to measure ambient supply air humidity levels. The basic layout and location of these sensors can be seen in Figure 3.

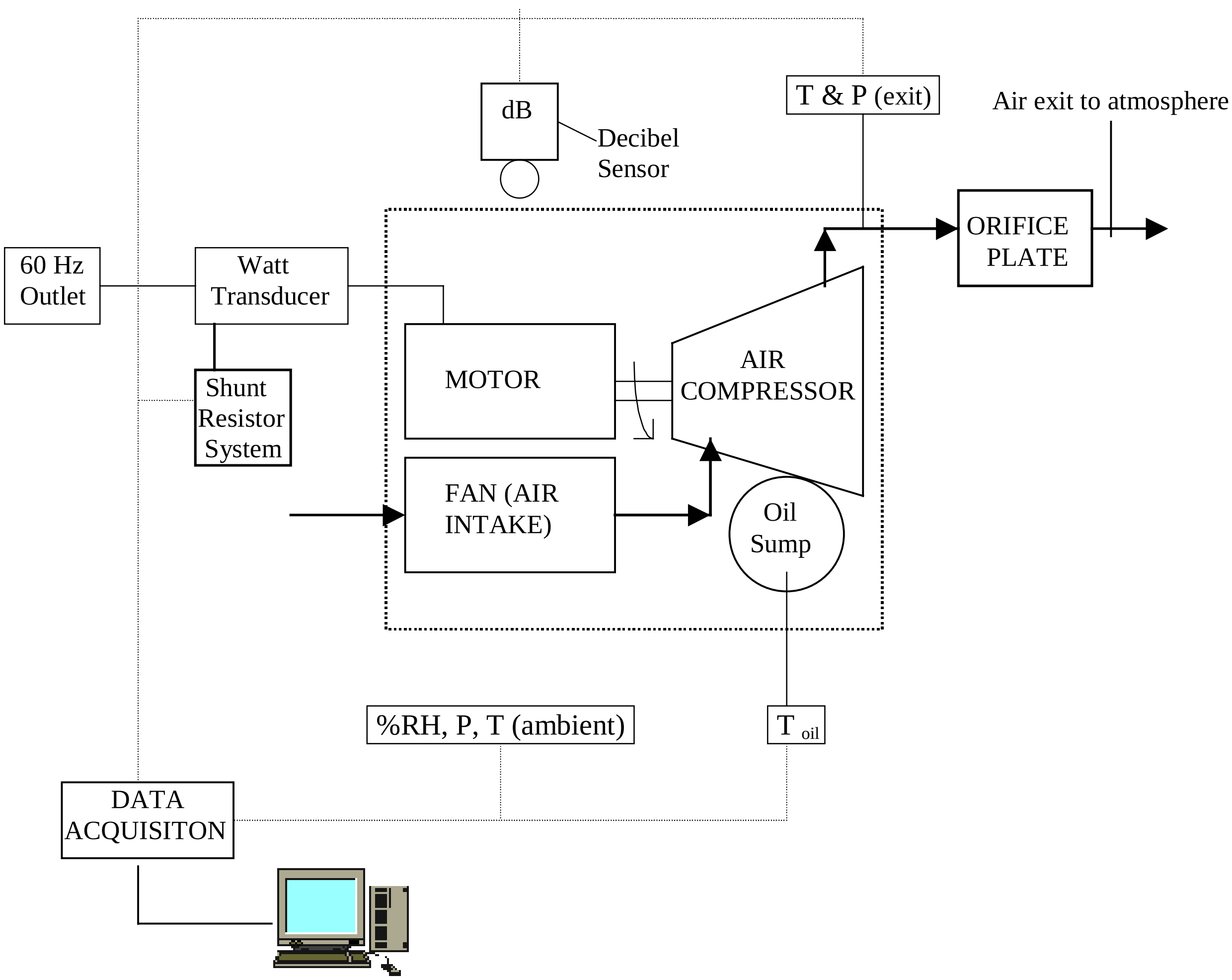

Figure 3. Schematic of the experimental setup to measure air compressor power consumption as well as environmental and operating conditions.

In addition, it was desired to obtain a measurement of the sound level produced by the operating air compressors by using a decibel sensor. The measurement of the sound level was of interest in order to determine if the lubricants were affecting the internal vibrations of the compressors significantly enough to alter the sound level emitted by the compressors. To do this, the student had to identify an appropriate decibel meter, incorporate it into the data acquisition equipment, and develop a uniform procedure for using this meter on each air compressor. This procedure involved primarily determining a location for placing the sound meter that would yield repeatable readings.

All of these sensors were connected to an industrial-type PC-DAS. The data acquisition unit is a Hewlett Packard HP 34970A system (Figure 4). This unit had three plug-in module slots to accept the data acquisition modules. A 16-channel reed multiplexer was used to accept the output signals from the instrumentation for the operating conditions and power consumption. HP BenchLink Data Logger software is used to provide an interface between the PC and the data acquisition unit. A 32MB RAM, 150-MHz Pentium-based PC with a 15” monitor, running Windows 95, was used as the PC unit. An industrial cart was used to store the PC-DAS and to provide mobility to each air compressor system.

Another part of this project had the student determine the properties of the tested commercial lubricants. Here, density measurements utilizing an accurate graduated cylinder and digital scale were made for each lubricant. Estimates of the lubricant's viscosity were obtained by a commercial ISO 9001 viscometer system. Table 1 lists the lubricants tested and the results of these measurements.

Table 1. Experimentally determined properties of tested lubricants.

LUBRICANT	DENSITY* (kg/m^3)	VISCOSITY* (cPoise)
Atlas Copco HD Rotofluid	842.7	78.9
Cochrane Compressor Corp. SynOil 825P	935.0	73.6
Royal Purple SYNFILM 32	842.7	57.1
Summit Industrial Products Inc. SH-68	865.2	115.6
Ingersoll Rand SSR Ultra	996.0	97.3

* Density and viscosity measured at 22°C.

Figure 4. PC-DAS and instrumentation used by students in the projects.

Project 2: Measurement of Air Compressor Power Consumption[2]

The second student project focused on the development and implementation of the power consumption instrumentation and the use of the entire data acquisition system to obtain complete measurements of the system operation. Two measurement devices were installed to measure the energy consumption of the air compressors. One technique involved measuring the voltage drop across a series of shunts, which is related to the current. This current is then multiplied by a voltage supplied to the device, a power factor for the motor, and a factor of three to account for the three-phase nature of the power. The primary purpose of this approach was to provide a check of the power measurement determined by using a commercial watt transducer. The watt transducer initially was built to measure power readings between 0 and 60 kW. The power consumption of the air compressor was in the lower end of the range, and so the supply voltage wires were wrapped around the current transformers in the watt transducer to reduce the usable range to 0 to 30 kW. This allowed for more precise measurement of the power consumption by the PC-DAS. This part of the experiment was most important since the primary goal of the overall project was to determine changes in the power consumption by the air compressors using different test lubricants.

This project also culminated in the use of the entire PC-DAS to measure the changes in energy consumption that could be achieved through the use of different advanced synthetic lubricants in the air compressors. These measurements were obtained by initially operating all of the air compressors with the same lubricant and obtaining a basic comparison of the energy consumption of the different compressors operating on this lubricant. Then, the original lubricant was flushed out of three of the compressors, and a different advanced synthetic lubricant was placed in each of the other compressors. The energy consumption of the air compressors operating on these lubricants was then measured, and the energy savings obtained for each lubricant was derived. Figures 5 and 6 are examples of the power consumption measurements for two different lubricants running in the same air compressor unit. In Figures 5 and 6, the plotted data represents the average of the measurements over the previous 30 minutes of operation. Under similar environmental and operating conditions, for these particular preliminary tests the average power consumed by the air compressor was reduced by approximately 0.68% when the advanced synthetic lubricant (Synoil 825P) was employed.

A FORTRAN computer program was written by the student to integrate and then average the large sets of data acquired during the experiments. This program reads the data set and places the different measured quantities into their own arrays. The data for each quantity is then integrated using the method of Gill and Miller[3]. This method allows the integration of unequally spaced data points through a third-order finite differencing scheme. The program allows for the removal of data sets with errors, and for the integration of only certain portions of the data. Therefore, either the entire data set can be integrated or analysis can be performed over discrete time segments (i.e., integrating and averaging every half-hour block of data). The program then saves the integrated averages of the data in output files which can be imported into a spreadsheet. For the energy consumption analysis, SigmaPlot 5.0, a technical graphics software package, was used by the student. This program was chosen because of its ease of use, ability to plot multiple axes on one graph, unlimited spreadsheet space, and professional quality graphs. The preliminary results from this study are shown in Table 2. After analyzing the data, it was determined that improvements could be made in the measurement and comparison procedure. These improvements are addressed in the fifth student project, described below.

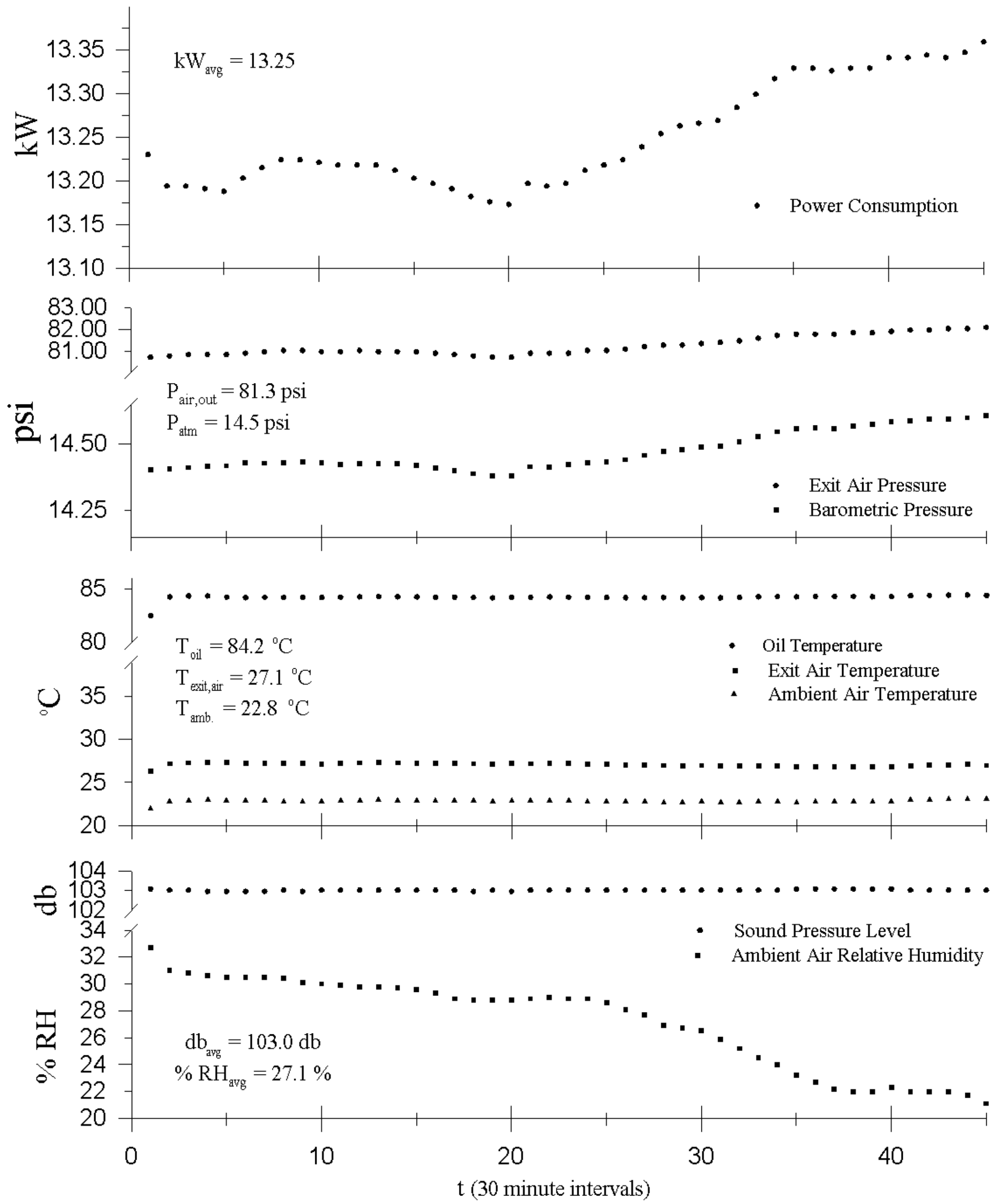

Figure 5. Average operating parameters for 30 minute intervals (Δt between scans = 10 s) of Compressor 2 with HD Rotofluid and Orifice Plate 2 for test runs on 4/22/99.

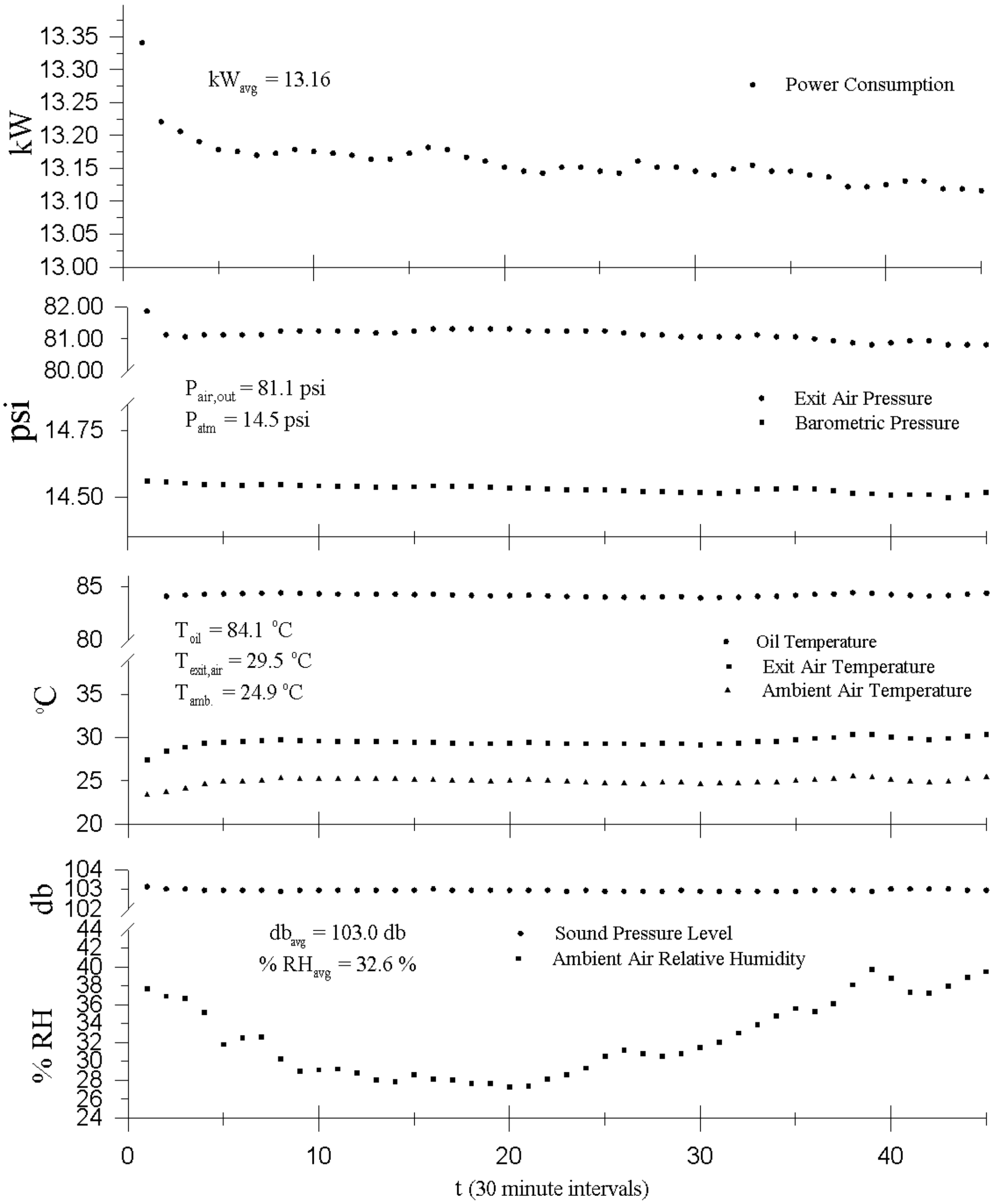

Figure 6. Average operating parameters for 30 minute intervals (Δt between scans = 10 s) of Compressor 2 with SynOil 825P and Orifice Plate 2 for test runs on 6/03/99.

Table 2. Preliminary energy consumption and cost savings for air compressor operation utilizing different synthetic lubricants.

Lubricant	Atlas Copco HD Rotofluid (Base Case)	Cochrane Compressor Corp. SynOil 825P	Summit Industrial Products Inc. SH-68	Royal Purple SYNFILM 32
Energy Savings	----	0.74%	1.37%	2.28%
Hourly Cost[1]	$0.9204	$0.9136	$0.9078	$0.8994
Yearly Cost[2]	$8063	$8003	$7952	$7879

[1] The base-case hourly cost was determined by considering a compressor operating on HD Rotofluid continuously consuming 13 kW of power. An energy cost of $0.0708 kW-hr was used in the calculations.

[2] The yearly cost is based on an 8760 hour year.

Project 3: Effects of Environmental and Operating Conditions[2]

The focus of the third student project was to determine which, if any, environmental factors significantly affected the energy consumption of the air compressors. This project was important for the identification of the environmental parameters whose changes would require the correction of the energy consumption measurements. If these changes with environmental conditions were not identified, all changes in energy consumption would have been inaccurately attributed to the use of different lubricants. Of particular concern was whether the environmental conditions for summer and winter operation would have a major effect on the air compressor performance.

A sample of some of the experimental data runs obtained as part of the project are shown in Figures 7 and 8. These plots show all of the measurements that are taken during a typical experiment. As expected the local barometric pressure, the ambient air temperature, and the relative humidity vary during the course of an experimental run. The most variable of these parameters is the relative humidity. Through the student's measurements, it was shown that the air compressor energy consumption was significantly affected by the relative humidity of the ambient supply air. For example, we see for an average relative humidity change from 10.8% (winter) to 41.1% (summer), an approximate decrease in power consumption of 1.8% exists for nearly identical conditions. Thus, the presence of water vapor in the air, which dramatically increases during the summer months, tends to reduce energy consumption by the air compressors. Changes in air temperature and pressure may also affect the energy consumption, but these are considered secondary and are typically much smaller during a given experiment, and throughout the year. The on-going focus of this project is to determine a correlation that can be used to directly relate the air compressor energy consumption to the water vapor content in the air.

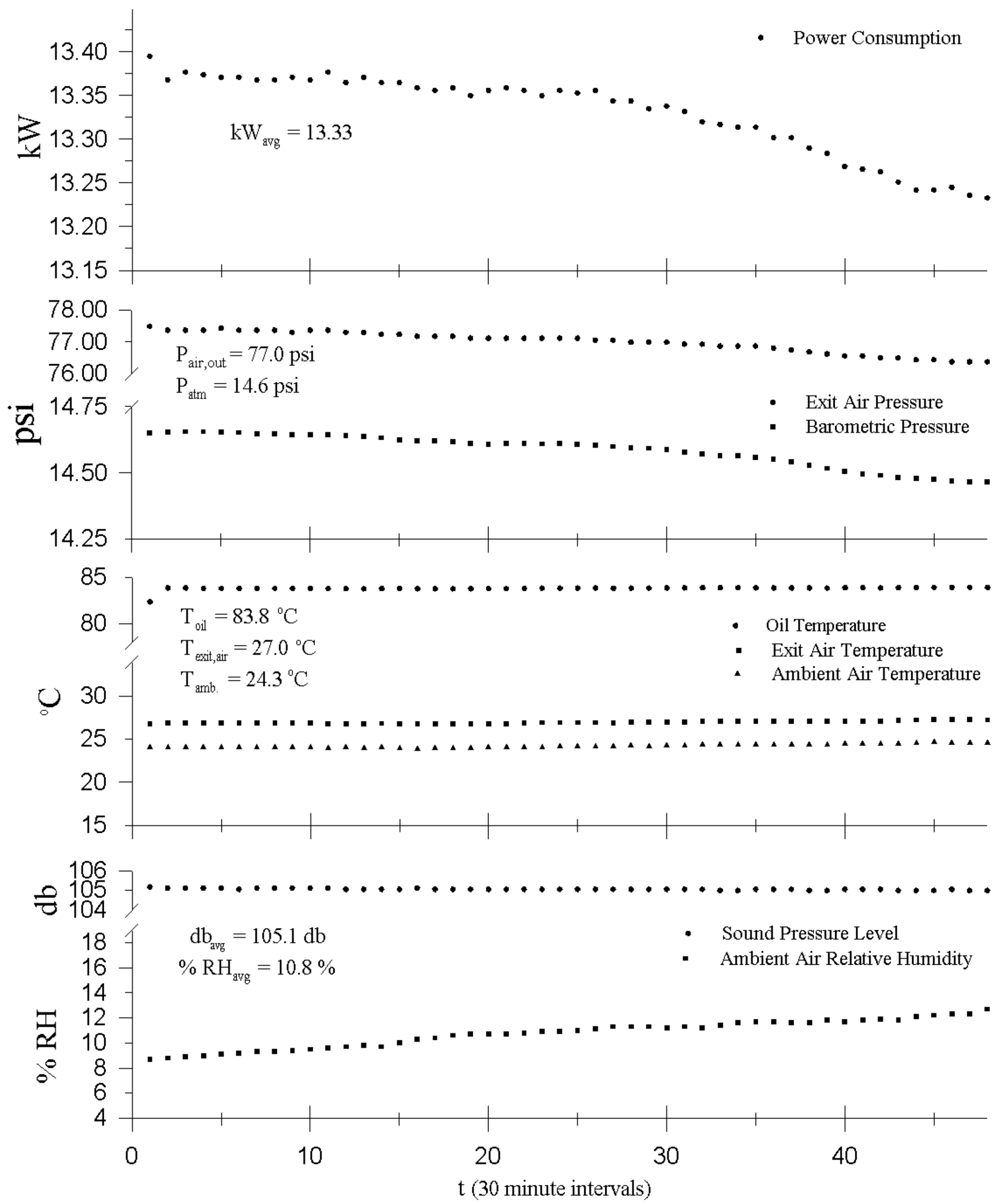

Figure 7. Average operating parameters for 30 minute intervals (Δt between scans = 10 s) of Compressor 3 with Royal Purple SYNFILM 32 and Orifice Plate 2 for test runs on 2/13/99.

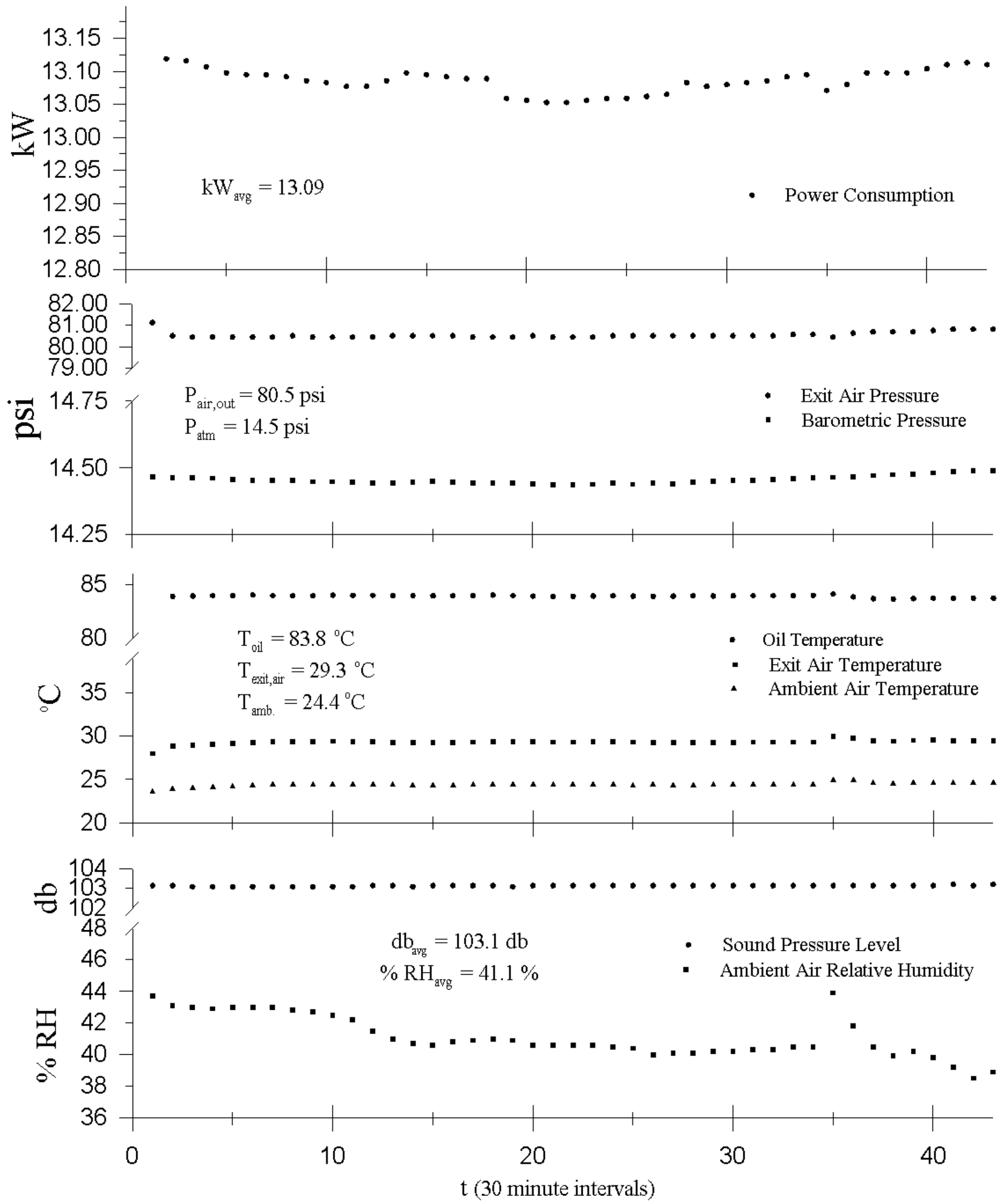

Figure 8. Average operating parameters for 30 minute intervals (Δt between scans = 10 s) of Compressor 2 with Royal Purple SYNFILM 32 and Orifice Plate 2 for test runs on 7/24/99.

Project 4: Thermal Analysis of Air Compressor Systems

The fourth student project involved the development of a method to analyze the dynamic thermal patterns of the air compressor system during operation. The objective of this project was to determine the relationship between high temperature locations or thermal "*hot-spots*" on the air compressor system versus operational time and employed lubricant. Here, the student designed a procedure to measure and analyze slight changes in temperatures across different components of the air compressor unit. A calibration procedure was developed as well as a method to accurately estimate the emissivity value of the surfaces. An Inframetrics Model 760 IR Imaging Radiometer with a Windows 95-based real-time imaging software package that monitors, records and analyzes transient temperatures was employed by the student (Figure 9). An example of the results that can be expected from this project are shown in Figure 10. Our current graduate Research Assistant is utilizing these procedures to record thermal profiles as part of a MS thesis.

Figure 9. Infrared thermal imaging radiometer system.

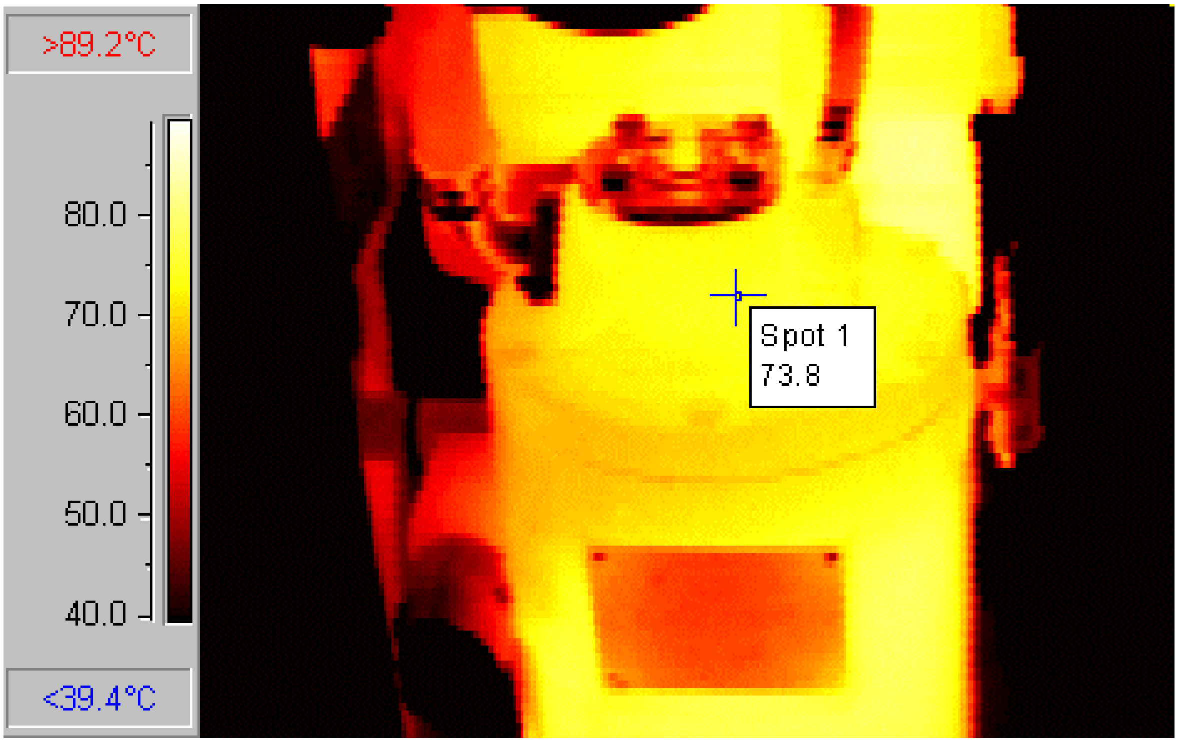

Figure 10. Exemplary infrared thermal image of air compressor during operation.

Project 5: Development of a Lubricant Changing Procedure[4]

Evaluation of the data from the energy consumption/savings measurements indicated that changes in procedures would lead to a more accurate determination of these savings. The primary change that was desired was to allow for greater comparison between the different lubricants on a single compressor. As discussed earlier, the preliminary measurements were performed by comparing energy consumption between air compressors using different lubricants, while considering compressor performance changes when all the compressors were using the base lubricant. It was determined that a much more effective procedure would be to test each lubricant in each compressor. However, this procedure requires a complete removal of all the lubricant between tests. Manufacturers of some of the tested synthetic lubricants claim that their product will permanently adhere to surfaces even after being drained. Therefore, a simple method to remove as much of the previous lubricant as possible was needed.

A procedure for changing lubricants was not found in the generally-accepted engineering standards. This indicated that we would need to develop a lubricant changing procedure. To aid us in this task, the student working on this project contacted several air compressor and lubricant company representatives for their input in this procedure. It was found that the general concern for these representatives was on the chemical compatibility of the different lubricants. It was suggested that if changing between lubricants of different chemical types (for example, if changing from a diester to a polyalphaolefin (PAO)) that a mineral oil flush be used. However, in this project to date, the basic chemical type of each lubricant is a PAO. The student's research determined that the appropriate changing procedure would be to use the following procedure.

(1) Drain the original lubricant from the compressor as thoroughly as possible.

(2) Fill the compressor with the new lubricant to be used in the test,

(3) Operate the compressor for several hours on this new lubricant,

(4) Drain the compressor of the new lubricant, which should also contain the remnants of the old lubricant.

(5) Change the oil filter.

(6) Fill the compressor with the new lubricant to be tested.

This single flush procedure should sufficiently cleanse the system of the old lubricant, such that any of the original lubricant would be at such low concentrations so as to negligibly affect subsequent tests. As a precaution, though, it is suggested that any lubricant which claims to adhere to surfaces after removal should be tested last in any given compressor. This project is currently being run in the *Air Compressor Experimentation Facility* and is part of our graduate Research Assistant's thesis work.

Project 6: Internet Web Page Development

The sixth of the student projects was the development of an Internet web page for the laboratory. This site was to describe the activities of the Energy Conversion Efficiency Laboratory, provide a place for the dissemination of experimental data once it had been acquired, provide an analysis of the data, and a public link to the public. This site (Figure 11) has been established at ***http://www.uwm.edu/Dept/Energy***. On this web site, the lab mission is thoroughly described, the experimental procedures are documented, the basic laboratory setup is presented, a comprehensive set of data for each compressor is provided, and the analysis of the current results is also given. In addition, some of the thermal images are available for viewing as well. This web site provides a resource for anyone interested in the effects of lubrication on air compressor energy efficiency.

Educational Experiences from Undergraduate Projects

The experiences gained by the undergraduate students working on these projects has been invaluable. The students were given the opportunity to work on a real-world engineering problem, similar to what they may encounter as engineers in the workforce. The students had to apply the knowledge learned in their mechanical engineering experimentation, thermodynamics, heat transfer, and fluid mechanics courses towards solving engineering problems. The students also needed to learn how to work together as a team by combining their particular specialties. The students were often working on different projects, each with a separate focus. However, successful completion of each individual project, as well as successful development of the laboratory, was only possible by joint solution of problems relating to overlapping projects.

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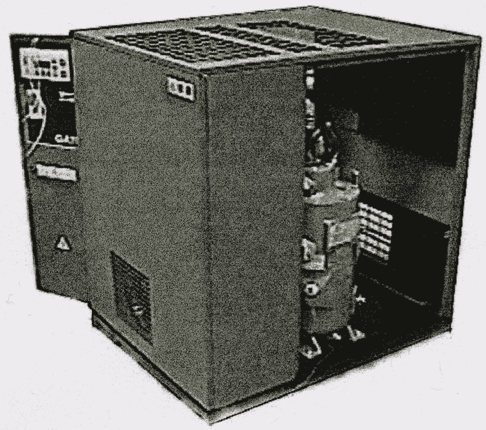

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COMPRESSED AIR CHALLENGE

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Please email Justin Edward Seipel (jestime@csd.uwm.edu) with any questions or comments about his web site.

Last modified: September 1st 1999

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Figure 11. *Air Compressor Experimentation Facility* Internet home page.

The students also were able to work much more extensively with experimental methods and industrial instrumentation than other undergraduates at the same level; this extends their coursework in the experimentation course required at UWM. The students gained additional knowledge about setting up experiments, determining the proper way to instrument the experiments, and how to interpret the results. The students also learned new experimentation techniques, such as using an infrared thermal imaging radiometer system. Data analysis computer programs were written and implemented, enhancing computer skills. In addition, the web page development also increased the Internet skills of the students.

Future Directions

We expect to continue to utilize both graduate and undergraduate student projects in the work of the *Energy Conversion Efficiency Laboratory*. Initially, we plan to implement the improvements to the energy conversion savings experiments, by using several lubricants in one compressor. We also plan to test additional lubricants. Directions for future laboratory development projects include in-line viscosity measurements of the lubricants, vibration analysis via use of an accelerometer, effect of lubrication as well as environmental and operating conditions on discharge mass flow rates, and branching the laboratory activities into new energy conversion efficiency problems. These problems will likely involve new hardware, which will present their own unique instrumentation problems. It is anticipated that this laboratory will be an ongoing source of new undergraduate projects.

Conclusions

The authors have found that undergraduate student projects can be employed to develop a state-of-the-art university-industry experimentation facility. These many projects have promoted national and international interest in our research work on air compressor energy efficiency via utilization of advanced synthetic lubricants. The undergraduate students gained knowledge and professional experience beyond what is provided by any undergraduate course in engineering at UWM. This industrial-like training included work in experimentation methods, data analysis, sensor technology, PC-data acquisition systems, IR thermal imaging, project management, and team-building skills. The outcomes of these student projects have resulted in a laboratory that can be easily adapted for use in several of our mechanical engineering courses.

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