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Abstract

Considerable effort was put forth on the mechanical design of the compressor section of the IEMDC. These efforts focused on the main compressor case design and included an evaluation of the motor-compressor interface. The initial mechanical evaluation of the compressor motor interface indicates that the integration of an electric motor and compressor can be made successfully. All mechanical design efforts resulted in considerable progress being made towards the completion of the mechanical design of the compressor section and towards the design of the IEMDC unit.

During the fourth quarter, one of the primary objectives was to select the magnetic bearing supplier and to begin finalizing the design of various motor components. Consequently, the design proposals from the three magnetic bearing suppliers were evaluated and Kingsbury Magnetic Bearings (KMB) was selected for the design of the magnetic bearing system. A purchase order was issued to KMB and design kick-off meeting was held at EMD on December 11, 2003 with the KMB/S2M/DR teams, to discuss the project requirements.

A joint DR/EMD/Robicon IEMDC Compressor-Motor-VFD Drive technical status update presentation was prepared, and was presented at the GMRC meeting on October 5, 2003 at Salt Lake City, UT. The presentation was attended by about 100 people and provided a very good feedback. Copies of the presentation were provided to DOE NETL and GMRC.

Considerable effort was expended in evaluating the fatigue life of the motor rotor via FEA modeling. The purpose of this analysis was two fold: 1) to establish the motor start-stop cycle life and 2) to evaluate the applicability of lower cost connection ring copper alloys. The FEA modal frequency analysis of relatively softer motor mount concepts instead of the hard mounts was continued. The intent of the design effort is to develop an optimum motor support. The results are not yet conclusive. Therefore further analysis is planned in the next quarter. The EMD design team worked with the KMB design team to develop design concepts for the magnetic bearing housings. Significant progress was made in interfacing the motor with the magnetic bearings.

Further work was continued on updating the motor outline, layout, and motor-compressor interface drawings. The completion of the DOE deliverables is continuing to be on schedule.

Table of Contents

List of Graphical Materials

Introduction

This report covers the fourth quarter (10/01/03 to 12/31/03) of the Phase 1 of the In-Line Electric Motor Driven Compressor (IEMDC) project.

The IEMDC project is the development of an in-line electric motor driven compressor to address the needs of the Natural Gas Industry. It represents a revolutionary advance in compressor system design and performance, in an improved package.

The objective of the first phase of the project is to develop the design of a direct coupled, seal-less, In-Line Electric Motor Driven Compressor to the point where detailed manufacturing drawings may be started. This gas compressor will be the world's first that can be installed directly in the pipeline, utilizing a variable speed induction motor with magnetic bearings that is integrated with a centrifugal compressor. It will be an electrically powered, highly flexible, efficient, low maintenance compressor that can be quickly ramped up to meet peak demands. The unit design proposes to provide low cost, low maintenance gas compression for the Natural Gas Industry while minimizing the environmental, regulatory, and maintenance issues associated with gas turbine drives by the use of an electric motor as the prime mover.

Executive Summary

Unit Configuration and Integration

The design and development process of mechanically integrating the compressor and motor gained significant progress during this quarter. Efforts during the design of the compressor section of the IEMDC included an evaluation of the motor-compressor interface. A preliminary interface design was created and a joint meeting was held between Dresser-Rand and Curtis-Wright to discuss relevant design considerations. This meeting was successful as a design approach was agreed upon to evaluate the mechanical interface joint. Both parties will perform an independent evaluation based on the design considerations that were discussed. Analytical studies were performed on this interface from the perspective of the compressor manufacturer. Results of the analysis indicated that the design is satisfactory to meet appropriate requirements and standards. This is a significant step in validating the feasibility of the mechanical design integrity of the unit.

A joint Dresser-Rand, Curtiss-Wright EMD and ASI Robicon presentation was made at the DOE Research Review Session of the Gas Machinery Research Council conference in Salt Lake City held in October 2003. This presentation provided an overview of the IEMDC project, which included the status of the technical design work, and progress made to date. The purpose of the presentation was to provide exposure to the project, receive feedback on the work being performed, and complete a deliverable of the award that requires a paper to be written and presented at a conference. There seems to be much interest generated by the project as the presentation was well attended. Copies of the presentation were provided to DOE NETL and GMR and posted on the GMRC Web Site.

A more detailed control and instrumentation schematic is being developed for the IEMDC as a deliverable of the award. This schematic shows the control arrangement of the IEMDC systems including the variable frequency drive, magnetic bearing control system, cooling gas conditioning skid, and unit control panel. The final schematic will be presented in the final project report at the end of phase 1.

Compressor Design

Mechanical layout and design of the compressor pressure containing case continued into the fourth quarter. Multiple design iterations were performed on the case design to achieve a proper balance between mechanical and aerodynamic requirements. Intermediate evaluations were performed using various calculation methods including numerical analysis techniques while designing the case to check the structural design integrity. The goal of the design was to achieve results that met or surpassed the requirements of relevant industry standards.

Structural analysis was also performed on mechanical compressor components such as the end wall, head, and necessary retaining devices. The results of the analysis were used to make determinations regarding the suitability of the design for applicable operating service conditions. Conclusions made from the analysis determined that the compressor components analyzed meet applicable criteria and are suitable for the intended operating service conditions. This results in achieving another significant step towards completing the design of the compressor section of the IEMDC.

Electric Motor

The motor design continued to make significant progress in the fourth quarter. One of the primary tasks to be completed was to select the magnetic bearing supplier and to begin finalizing the design of various motor components. Consequently, the design proposals from the three magnetic bearing suppliers were evaluated and Kingsbury Magnetic Bearings (KMB) was selected for the design of the magnetic bearing system. A purchase order was issued to KMB and design kick-off meeting was held at EMD on December 11, 2003 with the KMB/S2M/DR teams, to discuss the project requirements.

Considerable effort was expended in evaluating the fatigue life of the motor rotor via FEA modeling. The purpose of this analysis was two fold: 1) to establish the motor start-stop cycle life and 2) to evaluate the applicability of lower cost connection ring copper alloys (see Appendix C for discussion). The FEA modal frequency analysis, of soft motor mount concepts instead of the hard mounts, was performed. The intent of the design effort was to develop an optimum motor support. The results are not yet conclusive. Therefore, further analysis is planned in the next quarter. The EMD design team worked with the KMB design team to develop design concepts for the magnetic bearing housings. The magnetic bearing housings at the impeller and the thrust ends are depicted in the Addendum.

Further work was continued on updating the motor outline, motor layout, and motor-compressor interface drawings. The completion of the DOE deliverables is continuing to be on schedule.

In the next quarter, the focus will be to perform comprehensive design analysis of the motor-compressor interface, motor stator coils, magnetic bearing system, and motor wiring concepts. Further updates to the motor drawings and the DOE deliverables for Phase 1 will also be carried out.

In summary, during the fourth quarter, EMD has made significant progress in further completing the design of the 10 MW variable speed 12,000 rpm motor by selecting the magnetic bearing supplier and initiating the magnetic bearing system design, further evaluation of the modal frequencies of the motor mount system, motor start-stop cycle life evaluations, and updates to the motor drawings and the DOE deliverables. The IEMDC technical presentation at the GMRC conference in Salt Lake City provided a great opportunity to disseminate the IEMDC information to future prospective users. And the feedback was very favorable.

Experimental

No experimental work was performed during this reporting period.

Results and Discussion

Unit Configuration and Integration

A presentation was given at the GMRC conference in Salt Lake City on Sunday, October 5, 2003. This presentation was the first of several to be presented at the DOE Research Review Session of the Conference. An overview of the IEMDC project was given which included the status of the detail design work. In addition, the many merits of the design were reviewed including lower installed cost, lower maintenance cost, and the small footprint of the unit as compared to an equivalent gas turbine packages. Positive feedback was received on the presentation and work.

A more detailed control and instrumentation schematic is being developed from the write-up provided by Curtiss-Wright and shown in the third quarter technical report. This write-up included information about the VFD, motor control set-up, and magnetic bearing control set-up. Separate recommendations were also made regarding the set-up of the motor cooling gas flow control for the IEMDC unit. Integration of the controls systems and overall unit control is shown in the schematic. Additionally, the gas cooling loop has been added to the original schematic. This instrumentation and motor control schematic is a deliverable of the award. The final schematic will be presented in the final project report at the end of phase 1. A preliminary schematic is included in Appendix B. Packaging work and controls system integration is not yet complete, work will continue as information is received as the design of the IEMDC unit progresses.

Compressor Design

Mechanical layout and design efforts concentrated on the compressor pressure containing case and other major components. Multiple design iterations were performed on the case design to achieve a proper balance between the mechanical and aerodynamic requirements. These iterations resulted in the development of a case design for the compressor section. A conceptual three-dimensional model showing the IEMDC unit concept is shown in Figure 1.

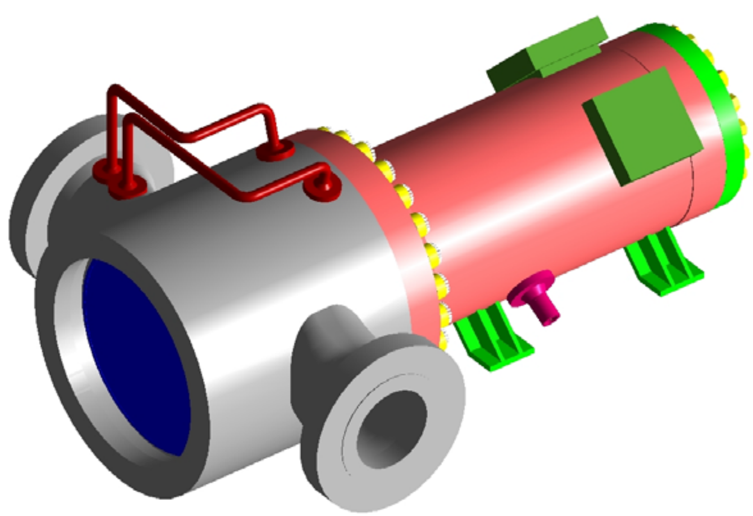

Figure 1. Conceptual IEMDC Unit

Calculations and analyses were performed on the case to check the structural design. These analyses consist of hand calculations and numerical calculations such as finite element analysis. Results of the analysis were reviewed in conjunction with relevant industry standards and requirements. Design criteria are established by the application of industry codes and standards related to the design of pressure vessels and compressor. Relevant codes and standards referenced during the design of the IEMDC compressor section case include API 617 and ASME BPVC Section VIII, Division 1 and 2. The evaluation of the design using the results of the analysis indicates that the design is acceptable for the intended service. Detailed results of these analyses are shown and discussed in Appendix A. Figure 2 shows a model of the case and head assembly.

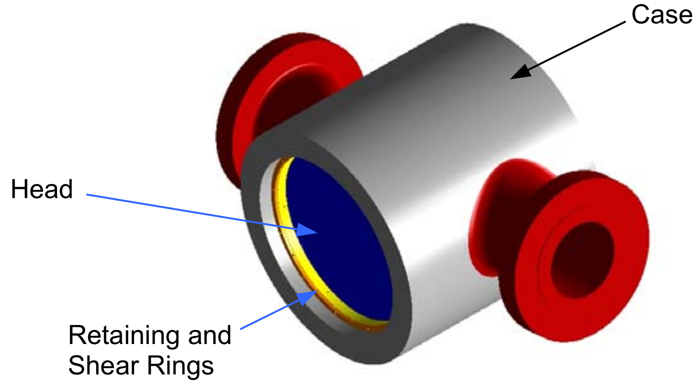

Figure 2. Case and Head Assembly

Structural analysis was also performed on mechanical compressor components such as the end wall, head, and necessary retaining devices (See Figures 2 and 3). The level of analysis used to evaluate a particular component design is selected based on the design criteria established for the component. Design criteria such as deflection and stress were considered. The results of the analyses were used to make determinations regarding the suitability of the design for the applicable operating service conditions. Conclusions made from the analysis determined that the compressor components analyzed meet applicable criteria and are suitable for the intended operating service conditions. Detailed results of the analyses are shown in Appendix A. Table 1 shows the expected design operating conditions for the unit developed for the performance specification deliverable of the IEMDC and used to develop mechanical design criteria.

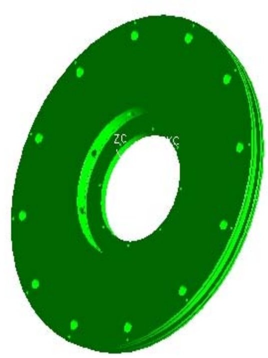

Figure 3. Compressor End Wall

Table 1
Expected Design Operating Parameters

Service	Natural Gas	----
Maximum Allowable Working Pressure	1500	psig
Maximum Operating Pressure	1200	psig
Inlet Pressure Range (typical)	500 to 800	psig
Discharge Pressure Range (typical)	700 to 1200	psig
Inlet temperature		
Typical	60 to 80	°F
Range	35 to 95	°F
Speed		
MCOS	12000	RPM
100% Speed	11429	RPM
Minimum Speed	8000	RPM

An evaluation was also performed on the mechanical interface between the compressor and motor case. A preliminary design concept was developed and a joint meeting was held between Dresser-Rand and Curtis-Wright to discuss relevant design considerations. Design considerations discussed included items such as leakage, deflection (rigidity), and clamping force. This meeting was successful as a design approach was agreed upon to evaluate the joint. Both parties agreed to perform an independent evaluation based on the design concept that was discussed. A follow-up discussion will take place to evaluate the results of the analyses. The compressor side evaluation of the interface concludes that the proposed interface is suitably designed for the expected operating requirements. A detailed analysis of the interface is provided in Appendix A.

Electric Motor Design

Selection of Magnetic Bearing Supplier: During extensive discussions of the design and project teams of EMD and Dresser-Rand the selection of the most appropriate magnetic bearing supplier was identified to be very critical for the successful operation of the IEMDC motor-compressor project. This is because the optimum design and operation of the magnetic bearings system is essential in locating the rotor critical speeds and the vibration response that would ensure design compliance with the requirements of the API standard 617, 7th edition for the centrifugal compressor and the API standard 541, 3rd edition, April 1995 for form-wound squirrel cage large induction motors. Furthermore, since the motor is designed to be cooled by the high-pressure natural gas from the compressor discharge, prior experience of the magnetic bearing supplier with verified designs in such an environment would be a plus. Considering these demanding goals, EMD had developed an internal 10-point merit system to narrow down the selection process. This objective system had been used successfully on another project.

The primary factors that were considered in the evaluation process were: design experience, commercial experience, cost, service experience, and manufacturing experience. Each of these items is described below briefly.

Design Experience: Pertaining to magnetic bearings, auxiliary bearings, control system, sensors, and rotordynamics analysis and its compliance with API standards.

Commercial Experience: This included level and extent of prior experience in designing and operating similar size magnetic bearing systems, in a similar high-pressure gas-cooling environment. How many systems were already operating in the field?

Cost: The one time cost of initial design for the prototype IEMDC, manufacturing cost of the hardware for the prototype, and cost of series production.

Service Experience: This included supplier's capability to provide after sales service, response time to address field problems, equipment warranty, and feedback from existing customers.

Manufacturing Experience: Were the manufacturing processes stabilized, how many systems of similar size have already been manufactured, internal rig test evaluations, lead time to ship hardware, etc.

The selection of the magnetic bearing supplier was indeed a very difficult process because all three suppliers that were being evaluated are technically very competent. However, using the selection criteria discussed briefly above, the three proposals to the EMD's RFQ, from the magnetic bearing suppliers (Waukesha Magnetic Bearings, Revolve Magnetic Bearings, and Kingsbury Magnetic Bearings) were evaluated and Kingsbury Magnetic Bearings was selected to design the magnetic bearing system for the IEMDC motor-compressor system. And consequently a purchase order was issued to KMB. Design kick-off meeting was held with KMB/S2M/DR on December 11, 2003 and the design work is now in progress.

Third Quarter Progress Reports: Detailed technical reports on the progress of the motor design were prepared and submitted to DR for inclusion in their report to the DOE.

GMRC Presentation: A joint technical presentation, by the team of DR/EMD/Robicon, was mad at GMRC conference on October 5, 2003 at Salt Lake City, UT. About 100 people from the various leading organizations, representing the Natural Gas Industry, had attended the presentation. The feedback that was received was very positive. Copies of the presentation were provided to DOE NETL and GMRC organization. GMRC had posted the presentation on their Web Site.

Evaluation of Motor Start-Stop Cycle Life:

FEA Modeling: The rotor end ring configuration plays a very critical role in determining the start-stop cycle life of the motor. Therefore several different design concepts were evaluated via FEA modeling to find the most feasible configuration. The stresses and displacements were calculated for the four different loading conditions described below. Necessary design modifications were implemented until acceptable levels of stresses and displacements were achieved for each case. Therefore the design process was very iterative.

-Assembly at room temperature (71F)
-Maximum running speed of 12,000 rpm at room temperature (71F)
-Maximum running speed of 12,000 rpm at maximum temperature
-Full operating temperature at 0-rpm

The basic design consisted of a circular array of copper bars imbedded in a solid steel shaft. The bars were held in place, in the radial direction, by a positive overlap between each bar and the shaft. A copper end ring was brazed to each end of the rotor bars. A high strength steel ring is shrunk fit over the copper connection ring to support it at speed. To reduce computational time, only a section of this configuration was modeled as shown in Figure 4.

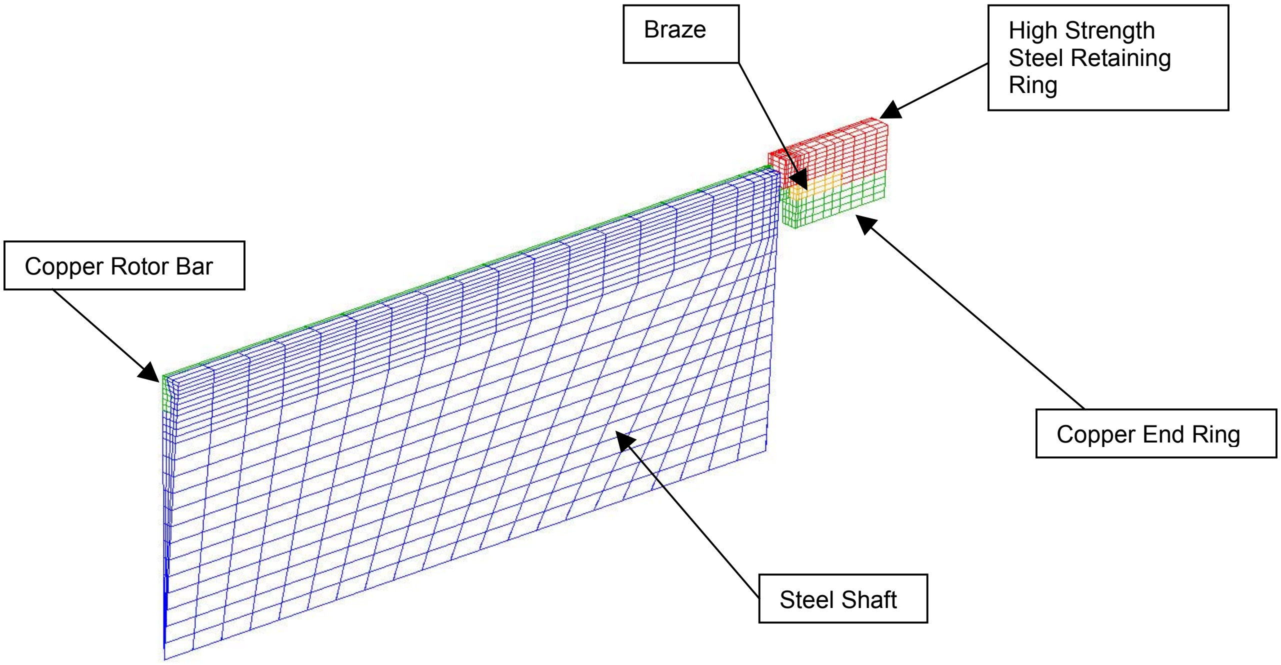

Figure 4: Finite Element Model of Rotor Section

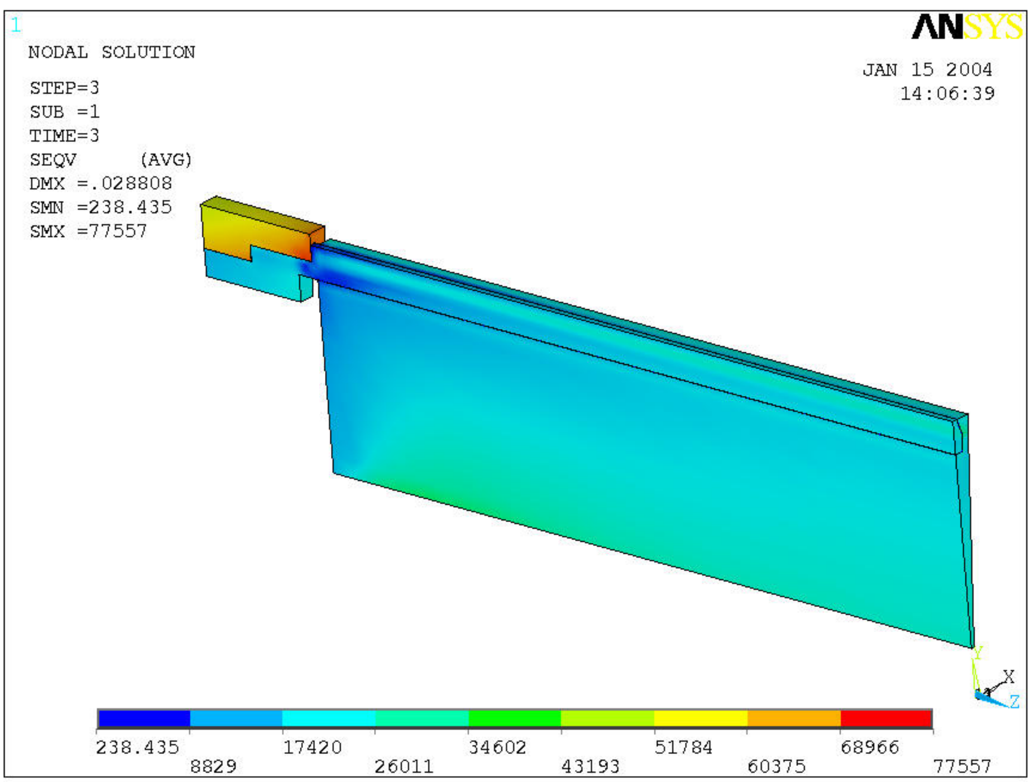

Figure 5: Predicted Von Mises Stress Contour Through The Various Rotor Components for the Case of Max Speed and Max Temperature.

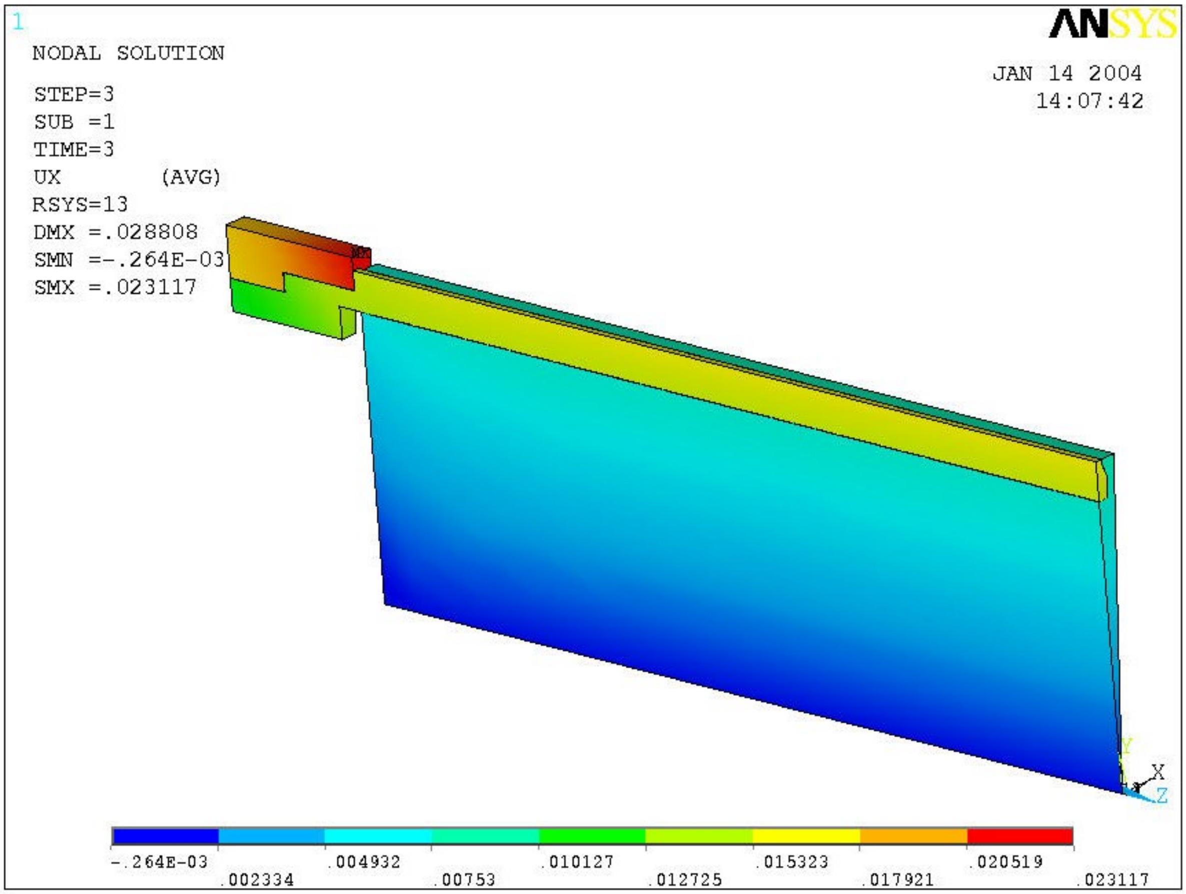

Figure 6. Predicted displacements at 12,000 rpm and Max temperature.

A more complete description of the motor life cycle calculations and discussion of the calculated stresses are provided in Appendix C.

Design Concepts for the Magnetic Bearing Housings:

The design teams of EMD and KMB worked together to develop design concepts for the magnetic bearing housings. Two such preliminary concepts, one at the impeller end bearings and the other at the thrust end bearings, are shown in the Addendum. These concepts will now be integrated into the motor compressor drawing. After this, FEA modeling of the housings will be developed, to calculate the housing stiffness, modal frequencies, and stresses, if required.

Conclusion

Work performed during the fourth quarter focused on the mechanical design and development of the IEMDC unit. Significant efforts were put forth towards completing the selection process for the magnetic bearings, developing a mechanical interface design concept between the compressor and electric motor, evaluating the fatigue life of the motor through analyses, and designing and analyzing major compressor components. These efforts show that considerable design progress has been made on the development of the IEMDC unit. Additionally, all efforts during this period demonstrate the feasibility of the IEMDC unit, system, and configuration.

The progress over this reporting period and the previous periods show that the technical challenges of the IEMDC configuration can be overcome and brings the concept closer to realization. Continuous development progress on the compressor and its components shows that the integration of the compressor and electric motor can be achieved. Multiple design iterations performed over the last four quarters continues to confirm the feasibility of an efficient and robust motor design for the 10 MW 12,000 rpm variable speed motor.

Furthermore, key design advantages of the IEMDC over conventional technology continue to be maintained. These advantages include several key industry attributes such as operational flexibility, remote operation and automation, efficiency, reduced maintenance issues, and environmental benefits. Magnetic bearings require no lubrication; the variable speed electric motor produces no combustion by-products, and a sealed design does not allow process gas to leak into the atmosphere. It also maintains the capability to be installed in-line with the process piping and potentially in an underground vault.

The evolution of the integrated motor-compressor design continues to confirm the viability of the innovative IEMDC system. This is a very significant achievement. The successful development of this new advanced technology integrated motor-compressor system would provide to the Natural Gas Industry, a competitive low cost and low maintenance gas compression alternative.

References

American Society of Mechanical Engineers, 1998, Boiler and Pressure Vessel Code, Section VIII, Division 1 and Division 2.

API Standard 617, 7th Edition, July 2002, "Axial and Centrifugal Compressors and Expander-compressors for Petroleum, Chemical, and Gas Industry Services".

API 541, 3rd edition, April 1995,"Form-Wound Squirrel Cage Induction Motors – 250 Horsepower and Larger".

List of Acronyms and Abbreviations

AF	Amplification Factor
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
BPV	Boiler and Pressure Vessel Code
CFD	Computational Fluid Dynamics
c.g.	Center-of -Gravity
DR	Dresser-Rand Company
EMD	Curtiss-Wright Electro-Mechanical Corporation (EMD)
F	Fahrenheit
FEA	Finite Element Analysis
GMRC	Gas Machinery Research Council
Hp	Horsepower
Hz	Hertz
IEMDC	In-Line Electric Motor Driven Compressor
I/O	Input / Output
kV	kilovolt
kW	kilowatt
kWh	Kilowatt hour
Lb	pound
Log Dec	Logarithmic Decrement
Mil	one one-thousands of an inch
MW	megawatt
PSI	Pounds per square inch
RFQ	Request for Quotation
RPM	Revolutions per minute
RTD	Resistance Temperature Detector
THD	Total Harmonic Distortion
V	Volts
VFD	Variable Frequency Drive