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HYDROGEN BLOWER DESIGN FOR FUEL CELL RECIRCULATION APPLICATIONS

INDEPENDENT ASSESSMENT REPORT

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration
- Transportation
- Energy Innovations Small Grant Program

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million, five percent of which is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)

- Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the California Energy Commission's website at http://www.energy.ca.gov/research/index.html.

Abstract

In order for the hydrogen fuel cell to live up to its potential as a clean, easily distributed electrical power generation, there is considerable work to be done in several aspects of system development. One area that has received little attention from industry is the development of ancillary fuel cell system components. This is especially true with regard to hydrogen-related (anode-side) components. H2Systems has proposed the development of a particular component that would conceivably improve the efficiency and decrease the cost of a small (1-10kW) PEM fuel cell system.

For proper operation, the hydrogen fuel cell must be supplied more fuel than is required for a given load. This results in excess hydrogen at the exit of the fuel cell stack, commonly known as anode tail-gas. The best way to use this extra fuel is to recirculate it back to the inlet of the fuel cell stack. The goal of this project was to determine the feasibility of using an H2Systems blower concept to achieve the hydrogen recirculation needs of a 1-10kW PEM fuel cell power plant.

There were four primary objectives associated with this project, including; construction of a prototype blower, the operation of this blower for 500 hours in a simulated fuel cell environment, characterization of blower performance, and projecting the manufacturing cost of the unit for the production volumes anticipated in the near future. Through successful completion of these objectives, it was determined that the proposed blower design is feasible for the described application, and should be further developed towards commercialization.

Key words: hydrogen recirculation, hydrogen blower, anode components, PEM fuel cell.

Introduction

Fuel cells promise to generate highly efficient, environmentally benign power for residential and small commercial markets. Cost reduction and improvements in cell-stack life are particularly critical for fuel cells to achieve acceptance in the market. The successful deployment of hydrogen fuel cells for power generation would reduce pollutants and greenhouse gases, as well as help alleviate constraints on electricity capacity and the transmission and distribution system in California.

A hydrogen recirculation system, if successfully developed for Polymer Electrolyte Membrane (PEM) fuel cells, would improve fuel cell performance, increase durability, and reduce the amount of platinum catalyst required to promote the anode electrode reaction. The project researcher estimated that the amortized value of the catalyst reduction alone could save $0.003/kWh over the life of a fuel cell. This enhancement could help fuel cells move toward economic viability. At that point the environmental, efficiency, and security benefits of fuel cells could produce significant market inroads.

Over the next 20 years, a successful fuel-cell initiative could result in 2 GW or more of PEM fuel cells in California. At a benefit of $0.003/kWh, the annual savings of the recirculation feature after 20 years of market penetration, excluding its impact on accelerating market adoption, is estimated at $30 million[1].

The researcher proposed a hydrogen recirculation blower that moves excess hydrogen at the exit of the fuel-cell stack (commonly known as anode tail gas) back to the inlet of the fuel-cell stack. The blower is a centrifugal design with a regenerative or “vortex” impeller configuration. The selected design has several attractive qualities: small size and weight; little-to-no maintenance; oil-free, adjustable electronic control; relatively low power consumption; and a wide temperature operating range. The unique blower design provides a method of pumping low-density fluids such as hydrogen, while maintaining a hermetically sealed containment of the process fluid. The availability of this technology could enable tail-gas recirculation with a cost-effective, “off-the-shelf” blower. The design is applicable to PEM fuel cells in the range of 1 kW to 10 kW. A fuel-cell process schematic incorporating the hydrogen blower is shown below.

[1] Assumes 5,000 full load hours of operation annually.

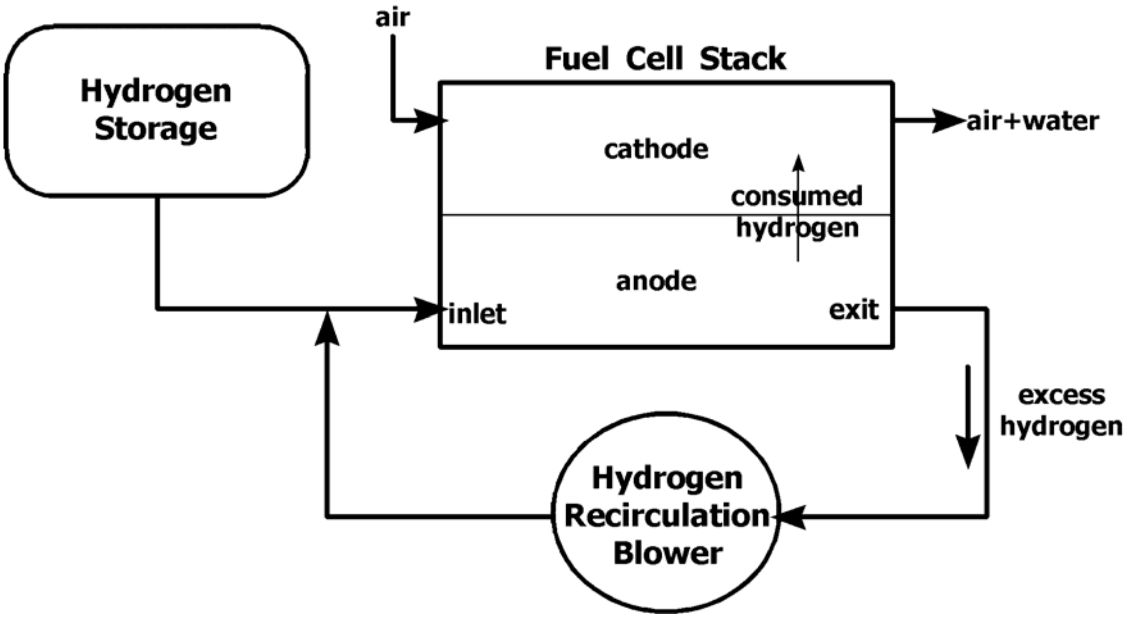

Figure 1: Hydrogen Blower Diagram

Objectives

This project was to determine the feasibility of using a centrifugal blower for the recirculation of anode tail-gas in a 1 kW-10 kW, hydrogen-fueled PEM fuel cell. The researchers established the following project objectives:

1. Construct a working prototype blower, capable of supporting the recirculation requirements of a 1 kW-10 kW PEM fuel cell.
2. Demonstrate 500 hours of operation in a humidified hydrogen environment without failure.
3. Verify that the blower is capable of achieving the following performance capabilities:
    - Can be mounted in any orientation.
    - Can function at motor temperatures of -30^{o}C to $+125^{o}$C.
    - Can maintain a maximum rotational speed of 35,000 rpm.
    - Can achieve projected flow rates and pressure differentials.
4. Project a manufacturing cost of $250 to $300.

Outcomes

1. A 7-cm-diameter blower capable of supporting 1 kW-10 kW fuel cells was designed. The blower components were selected (motor) and fabricated (impeller, housing, seals, tubes, and fasteners) according to the design specifications. The blower was assembled and successfully passed initial functional testing.

2. Under simulated fuel-cell operating conditions, pumping saturated hydrogen gas at 65 ^{o}C and 1.5 bar absolute, the blower performed without incident during a 500-hour test. Minor degradation was noted on the outside of the impeller fins and on a brass lock nut that was specified to be stainless steel.

3. Performance testing with three different blower orientations showed no difference in results. The researcher found neither start-up problems at –30^{o}C nor any performance degradation at temperatures above 100^{o}C. The unit demonstrated an ability to maintain a maximum 35,000-rpm speed for 8 hours. The flow-vs.-pressure drop was about 20 percent off the predicted performance. The energy consumption of the unit was measured at 59 W at maximum output, about 50 percent higher than projected.

4. The cost to produce the first blower unit was $941, with the motor accounting for $200. In high volumes (1,000–10,000 units), and with injection molding tooling, the researcher projected production costs at 20 percent of the prototype unit ($290).

Conclusions

1. The blower design proved to be functional, with parts either readily available or easily manufactured.
2. The blower prototype performed as designed under simulated fuel-cell conditions over a 500-hour period. Fixes to isolated component materials durability problems were identified. Future blower impellers will incorporate Ultem™ 1000,[2] an amorphous, thermoplastic polyetherimide that has demonstrated better compatibility with humidified hydrogen.
3. The following performance results were achieved:
    - The blower can be mounted in any orientation.
    - The unit can function at a wide range of motor temperatures demonstrating the ability to start up below freezing temperatures and to operate at high internal case temperatures.
    - The prototype unit can maintain maximum speed and flow rate for sustained periods.
    - The relationship of flow rate to pressure drop did not meet the original specifications and will require a design change for the impeller.
    - The power requirements were significantly higher than projected, warranting impeller-blade optimization to improve pumping efficiency.

4. The design lends itself to low manufacturing costs in modest production volumes. This project demonstrated that the proposed blower design is feasible and capable of meeting the functional and durability requirements for the recirculation of hydrogen in a 1 kW-10 kW PEM fuel cell. Component inspection after the durability test revealed little wear on the unit, indicating that much longer run times are feasible for this design. However, there were signs of wear on internal components made of Delrin® [3]. These components should be fabricated from an upgraded material in the design of the next generation.

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[2] Ultem™ 1000 was compounded with nano-fillers of carbon allotropes.

[3] Delrin® acetal resin emerged from DuPont's efforts to capitalize on the success of nylon and the growing post World War II market for plastics and other synthetic materials. Efforts to develop a tough and heat resistant metal substitute began in the early 1950s, and by 1952 chemists in the Polychemicals Department had synthesized an inflexible polymer from formaldehyde that assistant research director Frank C. McGrew called "synthetic stone" and DuPont named Delrin®.

Recommendations

The proposed recirculation compressor appears to address an important component gap among PEM fuel-cell developers. Further efforts should correlate performance with the newly refined computer model, should prove the material changes, and should verify durability of 5,000 hours

or more. Once these tests have been successfully completed, the researcher should establish partnerships with fuel-cell developers. The developers should integrate and test the compressor technology in prototype fuel-cell systems.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the program administrator has determined that the proposed technology should be considered for follow-up funding within the PIER program.

Receiving follow-up funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefits to the ratepayer from this research are reduced environmental impacts of the California electricity supply or transmission or distribution system. A commercially viable, hydrogen-fueled, fuel-cell power plant exhibits the near absence of pollutant emissions and greenhouse gases. This, along with its relatively high fuel efficiency, would make PEM fuel cells a preferred means of distributed-power generation. The hydrogen blower improves overall fuel-cell economics by reducing the operating cost. This should hasten the commercialization of PEM fuel cells.

Overall Technology Transition Assessment

As the basis for this assessment, the program administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

H2Systems has prototype units under evaluation with a number of stationary and automotive fuel-cell developers. These entities are the ultimate customers for H2Systems, Inc., and are their conduit to the marketplace.

Engineering/Technical

The project successfully demonstrated the functional performance of a hydrogen blower for PEM fuel cells. Enhancements have been identified that should improve the durability and performance of the next-generation prototype. The ongoing evaluations by fuel-cell developers should provide useful design and performance feedback to H2Systems, Inc. The next-generation prototype could benefit from a verification of the revised design model and an extended durability test. Ultimately, commercial prototypes will likely be customized for each fuel-cell developer.

Legal/Contractual

A patent on the hydrogen recirculation pump has been applied for. The title of the patent is: *Regenerative Pump for Hydrogen Gas Applications and Method of Using the Same*. The U.S. Patent Application number is 0023084 A1. The publication date is Feb. 5, 2004.

Environmental, Safety, Risk Assessments/ Quality Plans

It is too early in the technology development process to conduct formal environmental, safety, or risk assessments or to develop quality plans.

Production Readiness/Commercialization

The technology is under evaluation by a number of fuel-cell developers who will help H2Systems establish physical and performance specifications and timing for production units. This feedback coupled with H2Systems' identified fabrication techniques for high-volume production will enable the development of a Production Readiness Plan.

Appendix A: Final Report (under separate cover)

Attachment A – Grantee Report

HYDROGEN BLOWER DESIGN FOR FUEL CELL RECIRCULATION APPLICATIONS

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgements

H2Systems would like to thank R&D Machine Inc. of Poway, CA, and Mr. Harold Scofield in particular, for the excellent fabrication work on the blower components. Their precise work and attention to detail helped ensure the quality of the test unit.

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Abstract

In order for the hydrogen fuel cell to live up to its potential for clean, easily distributed electrical power generation, there is considerable work to be done in several aspects of system development. One area that has received little attention from industry is the development of ancillary fuel cell system components. This is especially true with regard to hydrogen-related (anode-side) components. H2Systems has proposed the development of a particular component that would conceivably improve the efficiency and decrease the cost of a small (1-10kW) PEM fuel cell system.

For proper operation, the hydrogen fuel cell must be supplied more fuel than is required for a given load. This results in excess hydrogen at the exit of the fuel cell stack, commonly known as anode tail-gas. The best way to use this extra fuel is to recirculate it back to the inlet of the fuel cell stack. The goal of this project was to determine the feasibility of using an H2Systems blower concept to achieve the hydrogen recirculation needs of a 1-10kW PEM fuel cell power plant.

There were four primary objectives associated with this project, including; construction of a prototype blower, the operation of this blower for 500 hours in a simulated fuel cell environment, characterization of blower performance, and projecting the manufacturing cost of the unit for the production volumes anticipated in the near future. Through successful completion of these objectives, it was determined that the proposed blower design is feasible for the described application, and should be further developed towards commercialization.

Key words: hydrogen recirculation, hydrogen blower, anode components, PEM fuel cell

Executive Summary

Hydrogen fuel cells hold the promise of Environmentally Preferred Advanced Power Generation. A distributed power infrastructure utilizing fuel cells would result in a significant environmental benefit in terms of pollutant and greenhouse gas formation, while at the same time reducing dependency on the fragile transmission network currently in place. However, for fuel cells to become commercially viable there is considerable work to be done in terms of technology development. The cost, durability, and availability of fuel cell systems must be improved to become competitive with established energy production methods. In order for this to be realized, significant advancements in stack design, hydrogen storage and production methods, fuel distribution infrastructure, safety codes and standards, balance of plant component development, and public education must occur.

One important area of fuel cell development that has not received adequate attention from industry is the technological advancement and invention of the ancillary (balance of plant) components necessary for proper fuel cell system operation. This is especially true with hydrogen-related (anode-side) components. Due to the unique demands of fuel cell operation, most “off the shelf” components are not appropriate for the PEM fuel cell application. In addition, with the current low demand for such components, there is little motivation for established manufacturers to enter into fuel cell component development programs. The result is that fuel cell manufacturers have largely been required to develop ancillary components in-house, which is highly inefficient and diverts resources from basic development programs.

H2Systems’ mission is to be a developer and provider of components and multi-component systems for use in the anode portion of the PEM fuel cell power plant. The goal of the company is to develop high quality hydrogen components that will allow fuel cell system developers to meet the demands of state-of-the-art fuel cell stack technology, and facilitate the emergence of the hydrogen-powered fuel cell as a commercially viable technology. This EISG project was proposed for the development of a particular component (Hydrogen Recirculation Blower) that is essential for the efficient operation of the hydrogen-fueled fuel cell power plant. Utilizing a blower of this type, the recirculation requirements for a 1-10kW PEM fuel cell could be improved over existing methods. The end result of this would be improved fuel cell performance, increased durability, and a reduction in the platinum catalyst required to promote the anode electrode reaction. These factors would correlate to an improved fuel cell that could be produced at a lower cost with longer lifetime. Amortized over the lifetime of the power plant, this would result in a significant reduction in cost of power generation.

The overall goal of the project was to determine the feasibility of using an H2Systems blower design for the recirculation of anode tail-gas in a 1-10kW hydrogen-fueled fuel cell application. Goal assessment was dependent on the completion of the following project objectives:

1) Construct a working prototype blower, capable of supporting the recirculation requirements of a 1-10kW PEM fuel cell.
2) Demonstrate the blower is capable of operating for 500 hours in a humidified hydrogen environment without failure.
3) Demonstrate that the blower is capable of achieving the following performance capabilities:
    - Can be mounted in any orientation.

- Can function at motor temperatures of -30°C to +125°C.
- Can maintain a maximum rotational speed of 35,000 rpm.
- Can achieve projected flow rates and pressure differentials.

4) Show that a projected manufacturing cost of $250-$300 can be supported.

The program was successful in completing the research required to evaluate each objective. A working prototype blower was constructed based on design parameters identified by pre-program modeling efforts. The fabrication and assembly of the unit was completed and the unit successfully passed functionality testing. While there were several iterations on some minor design issues, this portion of research proceeded without noteworthy incident. A 500-hour durability test under fuel cell operating conditions was successfully completed to demonstrate component lifetime and assess potential failure modes. The prototype blower completed this portion of research without malfunction, and several areas of design improvement were identified. An experimental test plan was executed to assess component performance capabilities, including operating temperature range, maximum sustainable rotational speed, the effect of orientation, as well as flow rate and available pressure head. During this portion of research, the only unexpected result was an approximate 20% difference seen between experimental flow rate and pressure data and predicted (pre-test) performance values. This variance can largely be attributed to the difficulty in predicting centrifugal pump performance without design-specific empirical data. Therefore, the observed discrepancy was not due to an inadequacy of the hardware, and does not have an appreciable effect on the feasibility of the design. A cost analysis of the blower was also completed. This was based on the prototype unit cost and projected savings for anticipated near-term production volume. This analysis projected the cost of the unit to be $289 when produced in volume of 1000 units or more, and satisfied the final objective of the project.

By successfully completing the objectives in the manner described, it was concluded that the blower prototype under consideration is a feasible design for the target application. While there are clearly areas of improvement that were noted through the course of research, there were no impassable barriers identified that would preclude further development and eventual commercialization of this component. Moreover, successful development of this component would likely facilitate the emergence of the PEM fuel cell as a commercially viable technology.

The next step in the development of the H2Systems Hydrogen Recirculation Blower is the construction of additional prototype devices based on the refined modeling capabilities resulting from EISG research. Since the demonstration of a scalable device would result in greater flexibility for potential customers, a parametric study to verify the effect of various design changes would be beneficial. In addition, extended durability testing is required to prove the usefulness of the device in a practical application. Finally, with the success of this project, H2Systems is now prepared to seek partnerships with fuel cell system developers and manufacturers to further advance the technology and obtain performance data from an actual fuel cell system. All of these steps are seen as necessary for the commercialization of the technology, and will result in a product that provides for a need of the fuel cell system manufacturer.

The public benefits to California, not to mention the United States, of the emergence of the fuel cell as a commercially viable technology are widely touted and well known. The technology being researched under this EISG grant will result in a fuel cell system that is less expensive, more reliable, and more durable. Only through the continued improvement of these aspects of fuel cell technology will the benefits that it promises someday become a reality.

Introduction

The goal of this project was to determine the feasibility of using an H2Systems blower design to meet the recirculation requirements for a 1-10kW hydrogen-fueled fuel cell. The success of this project was based on the ability of the hardware to demonstrate achievement of the project goal. This was illustrated through completion of the project objectives. The objectives consisted of the construction of a hydrogen recirculation blower, a demonstration of the ability of the blower to the meet the performance, functional, and durability requirements of hydrogen fuel cell operation, and an analysis showing this unit could be produced for under $300 as projected in the original proposal.

The net result of effective recirculation in a hydrogen fuel cell is a reduction in the amount of platinum catalyst required for proton generation. Since platinum is very expensive, this results in significant savings in the cost of each fuel cell unit. H2Systems has calculated that compared to no recirculation at all, a fuel cell with proper recirculation could cut anode catalyst material costs by as much as 25%. This would result in estimated savings of $0.003/-kWh over the life of the power plant. This saving could be directly transferred to California consumers.

Project Objectives

The project objectives are the criteria on which the success of the project was based. The objectives listed in the proposal were:

Objective 1: Construct 7cm (approximate) blower prototype capable of supporting PEM fuel cells in the range of 1-10kW.

Objective 2: Demonstrate the proposed design is capable of operating 500 hours in a humidified hydrogen environment without malfunction.

Objective 3: Demonstrate that the proposed blower design is capable of achieving the following performance capabilities:

(1) Can be mounted in any orientation.
(2) Can function at motor temperatures of –30°C to 125°C.
(3) Can maintain rotational speeds of at least 35,000 rpm.
(4) Can achieve the projected flow rates and corresponding pressure differentials as depicted in the proposal.

Objective 4: Show that the projected manufacturing cost of $250 to $300 can be supported.

Project Approach

Project Task 1: Construct Prototype Hydrogen Blower

The first objective of the project was to construct a 7-cm diameter blower that would be capable of supporting a PEM fuel cell with a 1-10kW output. The design and dimensions of the blower were developed based on a previously established proprietary concept utilizing an H2Systems modeling program. The motor to drive the blower was selected based on size, available torque, rotational speed, and performance specifications. The required ancillary components were identified and procured.

An interview process queried several local machine shops for the ability to manufacturer the necessary components within the required tolerances. Drawings that were produced from the model were then submitted to the selected machine shop for fabrication of the components. All the necessary components were acquired and photographed. Pictures of the blower components were submitted to the EISG Program Administrator before the program proceeded.

The components of the blower were inspected prior to assembly. Measurements were taken of the clearances for the impeller, including the axial and radial runout. The gap from the impeller to the housing was set within tolerance. After assembly, the unit was pressurized and monitored for external leakage. The initial leak rate was determined to be within acceptable limits. The unit was then tested for basic functionality before proceeding with the design verification test plan.

Project Task 2: Design and Construct Experimental Test Stand

A test stand was designed with the ability to operate the blower assembly under simulated fuel cell conditions and to perform the required test procedures. The components and instrumentation required to complete this task were identified. The objective was to demonstrate the recirculation requirements of the blower while holding the working fluid (hydrogen) within a temperature and pressure range consistent with typical fuel cell operation. This fluid would be required to maintain a fully saturated condition. Because this station would be using hydrogen gas, it was essential that external leaks be minimal. The test station was designed so that the entire system would be hermetically sealed.

The required components for the test station were then procured. The system required stainless steel tubing and Swagelok® fittings to achieve the required system integrity. A flowmeter was included to measure the flowrate and a differential pressure gauge to measure the pressure rise between the blower inlet and outlet. A stainless steel ball valve was used to induce pressure fluctuations (system resistance) to the blower. Hydrogen was supplied to the system from an external tank through a 2-stage pressure controller and two valves. An external resistance-heating element with controller was used to control the temperature of the working fluid. A humidification reservoir was required along with a resistance heater and controller. Thermocouples were chosen to monitor the temperatures and pressure gauges were used to record the system pressure. A differential pressure gauge was used to measure the pressure rise across the blower inlet and outlet. A vacuum pump was required to evacuate the system, allowing the required hydrogen composition to be achieved. A schematic of the system is shown in Figure 2.

The test station was then constructed and commissioned to confirm function and measurement accuracy. The hardware and instrumentation were assembled and the system tested to verify functionality and operation. The absolute and differential pressure gauges were calibrated using a manometer, and the flow meter was calibrated using a venturi meter. The system integrity was verified for external leakage using hydrogen gas at 1.5bar absolute pressure. The initial leak rate was established for the system, and found to be within acceptable limits.

Project Task 3: Develop Experimental Test Plan and Deliver to Program Administrator for Approval

A test plan to demonstrate the performance and durability capabilities of the blower was developed. This plan incorporated two of the project objectives, which collectively demonstrated the blower’s performance and durability. The plan specified the tests that would be used to evaluate the blower for performance testing, orientation sensitivity, low and high temperature testing, high-speed operation, and humidified hydrogen operation testing. The criteria used to determine the successful completion of the objectives was also specified. Additionally, the test plan outlined the pre-test inspection of the blower and the post-test evaluation used to determine degradation, wear, or loss of function. The test plan was submitted and approved by the EISG Program Administrator.

Project Task 4: Conduct Experimental Research to Prove Concept Feasibility

Based on the test plan submitted for approval, the individual test procedures were established. A test schedule was then developed that would systematically complete the test requirements. The test plan was then executed in logical sequence.

Pre-test evaluations were performed as a baseline. These evaluations established the conditions of the components prior to testing and the leak rate of the blower unit.

The unit was first tested for performance. Tests were conducted with air (density 1.2kg/m3), with dry hydrogen (density 0.08kg/m3), and humidified hydrogen at 60°C (density 0.20kg/m3). These fluids were used as the standards for measuring performance and degradation. Figure 3 shows the initial performance of the blower with these fluids.

Performance curves were also run at the completion of each of the tests listed below to assess any degradation from that particular test. Due to the lack of degradation, as would be depicted by a drop in performance, only the final post-test performance curves are presented.

The blower was tested for orientation sensitivity. The blower was rotated and run at 25,000 rpm for 25 hours at each of three different orientations. Each orientation was 90 degrees of the previous test position. The working fluid was humidified hydrogen pumped at 3.7 CFM.

To confirm freezability of the unit and cold start operation, the unit was placed in an environmental chamber at -30°C for 8 hours and then run under normal conditions for 8 hours. This procedure was repeated 5 times. To minimize start up times, this test was run with air at 3.5 CFM.

Because the motor is the component most sensitive to high temperature damage, the unit was run for 24 hours with an internal motor temperature of 125°C. This demonstrated the high temperature durability of the unit. Because of the high torque requirement to attain this temperature, the test was run with air as the working fluid at 3.9 CFM.

To demonstrate that the blower can sustain maximum operating conditions, a test to demonstrate the ability of the blower to maintain a rotational speed of 35,000 rpm for 8 hours was then performed. This test was run in a closed system with hydrogen maintaining a flow rate of 6.0 CFM.

Finally, the blower was tested for 500 hours of continuous operation under simulated fuel cell operation. The system was held at 68°C +/- 8°C and 1.5bar +/- 0.2bar absolute using fully saturated hydrogen as the working fluid. The blower was held at 24,000 rpm (70% load) and its performance was initially measured at 3.5 CFM at 35mbar pressure rise.

To humidify the fluid, an internal water reservoir was utilized. To ensure saturation the temperature of the reservoir was controlled at 2°C above that of the working fluid. The temperatures of the reservoir, working fluid, and motor were monitored during the test as well as the system pressure and the flow rate of the blower.

Due to the leak rate of the system (0.08cc/min), hydrogen needed to be supplied periodically, in order to maintain system pressure. The system was enclosed in a chamber to help maintain a constant temperature. The speed of the blower was constant throughout the test.

Upon successful completion of the tests, final performance curves were run with air, dry hydrogen, and humidified hydrogen at 60°C. These curves were compared to the initial curves to evaluate degradation of performance. Figure 4 shows a comparison of the performance curves used to determine the degradation throughout the testing procedure. A final leak rate for the blower was then established using hydrogen at 1.5bar absolute. The unit was then disassembled and inspected for unusual wear, degradation or hydrogen embrittlement. Pictures were taken to verify the condition of the components, as shown in Figures 5 and 6.

Project Outcomes

Blower Design, Construction, and Assembly

The design of the blower, based on a model developed at H2Systems proceeded very well. CAD drawings of the blower components were developed and then delivered to the chosen fabrication shop and returned in a timely fashion. The motor chosen for the project produced the required output and performed well. The fabricated components matched the drawings and the unit was assembled without issue. All tolerances were within specifications. Initial conditions of the components were documented with photographs. The impeller was set with a working gap of 0.2mm and showed a total runout of 0.05mm. The initial leak rate of the assembly at 1.5bar absolute of H2 was 0.08cc/min A picture of the blower components is shown in Figure 1. The blower successfully passed the initial functional testing without incident.

Demonstrate 500 hours of Operation in a Humidified Hydrogen Environment

One of the primary objectives of the project was to demonstrate that the blower could pump humidified hydrogen at a specified rate for 500 hours without malfunction. The blower was installed on the test station that simulated fuel cell operating conditions. The objective of this test procedure was to complete 500 hours of continuous blower operation while pumping saturated hydrogen gas at 65°C and 1.5bar absolute.

The blower performed without incident during the entire 500-hour test. The speed of the unit held constant and the only changes in flow rate were consistent with variations in the pressure and density of the fluid. No degradation of function was observed during the procedure. Post test evaluation indicated no loss of performance.

The completion of this procedure demonstrated the robustness of the design, and the ability of the hardware to meet the durability objective paramount to the success of the project. Upon disassembly, the blower did not display any significant signs of degradation, as depicted in Figure 5. The bearings on the motor appeared to exhibit some indication of play, but this was difficult to quantify (less that could be measured with a dial indicator).

An observation noted upon tear down of the unit was a build up of a white powdery substance on the outside of the impeller fins. This was attributed to a break down of the Delrin™ material chosen for the internal components of the blower. Although Delrin™ (acetal) is reported to be compatible with the fluids used in this project, there appears to have been degradation of the material. Future blowers will be upgraded with ULTEM™, an amorphous thermoplastic polyetherimide, which has demonstrated compatibility with humidified hydrogen.

The locking nut used to secure the IP 68 electrical connector inside the sealed unit was the only component that showed a marked change over the test period. Although the nut was believed to be stainless steel, investigation revealed it was a nickel-plated brass material. Corrosion of the base material was evident by a green crystal formation on the component as shown in Figure 6. This nut was exposed to the working fluids during these tests, and showed an incompatibility with the humidified hydrogen during the 500-hour test. The inclusion of this material was an oversight, and would not normally be used in this application.

Demonstrate Capability of Achieving Functional Targets (Performance Capabilities)

- Can be mounted in any orientation

The functional test of operating for 25 hours under each of three different blower orientations was performed as described. The performance testing in these orientations supports insensitivity of the unit to mounting orientation. Pre- and post-test performance curves were identical, indicating no degradation or loss of performance was associated with this procedure.

- Can function at motor temperatures of -30°C to +125°C

The -30°C is a requirement for the blower assembly as well as the motor. It is important that the unit be subjected to cold temperature extremes without degradation. It is also important that the unit demonstrate the ability to start up at below freezing temperatures without hesitations or lock up. After 8 hours of exposure to -30°C conditions, the blower was immediately placed on a test stand to initiate start up and 8 hours of normal operation. This procedure was repeated 5 times. No degradation or start-up issues were experienced during this procedure. Post-test procedures indicated no loss of performance associated with these tests. The +125°C requirement is primarily for motor capability, since the working fluid of a fuel cell should never see that temperature. For this test, the temperature of the motor case was recorded and the actual internal temperature of the motor was calculated, based on the heat transfer coefficients given by the motor manufacturer. Under the test conditions, it was determined that a case temperature of 100°C would result in an internal motor temperature of 125°C. The unit was stabilized at a speed of 25,000 rpm pumping air at 3.9 CFM to achieve this condition, and held there for 24 continuous hours. This successfully demonstrated the ability of the motor to sustain this temperature. No degradation was observed during the testing. Post-test procedures indicated no loss of performance associated with this test.

- Can maintain rotational speeds of 35,000 rpm

To achieve the maximum pressure rise capability of the blower, the maximum rotational speed must be utilized. It is important that the unit demonstrate the ability maintain that speed for sustained periods of time without failure or degradation. Completion of 8 hours of operation at 35,000 rpm while pumping hydrogen at a flow rate of 6.0 CFM confirmed the ability of the unit to maintain sustained maximum speed operation. No degradation was observed during the testing. Post-test procedures indicated no loss of performance associated with this test.

- Can achieve the projected performance depicted in the initial proposal

The projected performance of the blower was specified in the original proposal, based on a computer model using the parameters chosen for this design. It specified the performance of a fluid with a density of 0.20kg/m3 (humidified hydrogen at 60°C) as shown in Figure 7. The actual performance of the test blower with this fluid demonstrated an approximate 20% variation from the predicted performance values. This performance difference was not due to a fault in blower function. It is attributed to an inability of the model to predict actual hardware performance based on design parameters. As seen by a comparison of the performance curves shown in Figure 7, the hardware achieved a higher than expected flow rate, with a lower pressure rise than predicted. Refinement of the model shows that increasing the impeller diameter by 2 mm and reducing the fin radius by 1mm would be required to achieve the projected curve.

While the performance of the actual hardware did not match the projection, it would meet the recirculation requirements for a 1-10kW PEM fuel cell. It is important to note that every fuel cell design has a unique set of requirements based on its specific design. The performance parameters originally chosen were not arbitrary; however, they are not the only set of conditions to satisfy a 1-10kW fuel cell. It is as likely that a 1-10kW fuel cell would have recirculation requirements that would be met by the prototype hardware as it would have by the performance stated in the initial proposal.

Energy consumption of the unit was measured and found to peak at approximately 59W at maximum output. Estimating the combined efficiency of the motor controller and motor to be 68%, this would relate to 40W of work on the fluid under full load. Although this is a modest parasitic requirement, the figure is about 50% higher than the theoretical minimum required to achieve the demonstrated performance. As a follow up to this project, an optimization of the impeller blade design could be undertaken to improve the pumping efficiency of the unit.

Demonstrate the Projected Manufacturing Cost of $250 to $300 can be Supported

The blower used for this project was a unique unit, made from off the shelf components or those fabricated by machining bulk materials. The cost to produce this unit was $941 with the motor accounting for $200. The majority of the cost reduction for producing this blower in high volumes would be in the fabricated components. By purchasing injection molding tooling the working components could be produced and assembled with little machining. With high volumes, the tooling would be amortized, and the production costs are estimated at 20% of the current costs. For several components, this is a conservative estimate. The machined endcap was delivered at a cost of $78. A similar molded part with the same complexity can be purchased at a supply store for $5. For other components, such as the impeller, the injection-molded part may not attain the full projected reduction.

In production volumes, the purchased components would be reduced on a high volume basis. For example, a quote on the motor for quantities of 1,000 units was $125/unit, approximately a 40% reduction from the single unit cost. A similar reduction could be expected for most of the purchased items at higher volumes. Utilizing the savings projected for high volume manufacturing (1,000-10,000 units), it can be demonstrated that the cost of this blower is projected to be approximately $289. Table 1 shows a component breakdown of the projected unit costs.

Conclusions

Through the completion of this project, it has been demonstrated that the H2Systems blower design is feasible of meeting the functional and durability requirements for the recirculation of hydrogen in a 1-10kW PEM fuel cell. The design, based on a proprietary H2Systems concept, was fabricated and assembled without complication. The performance of the blower did not match the projected performance, but did demonstrate feasibility of meeting the recirculation requirements of a 1-10 kW PEM fuel cell.

To be suitable for fuel cell applications, a component must demonstrate the ability to perform for extended periods of time under actual operating conditions. A test plan was devised to demonstrate the ability of the blower to withstand typical fuel cell operation conditions. With the completion of the 500 hour humidified hydrogen durability test, the blower met a paramount obligation of the project. A post-test inspection of the components revealed that there was little wear on the unit, indicating that much longer run times are feasible for this design. However, there was a white substance noticeable inside the fins of the impeller. This was attributed to a breakdown of the Delrin™ material chosen for several of the internal blower components. For commercial use, this material will be upgraded. A cost analysis was reported which showed this blower would be capable of being produced in high volumes for approximately $289. This is within the cost range suggested in the proposal.

Recommendations

Because it is important to verify the correlation between model predictions and hardware performance, a new blower should be constructed based on the newly refined computer model. After demonstrating the ability to match performance objectives, the new unit should undergo an extended durability test. The test should be the same as the 500-hour humidified hydrogen test, except with a goal of 5,000 hours. With the success of this project, feasibility of this technology has been established. H2Systems is now in a position to seek development partnerships with current fuel cell manufacturers to further advance the technology and to obtain actual fuel cell performance testing. This would be the most likely path toward commercialization of the technology.

Public Benefits to California

The primary benefit of a commercially viable, hydrogen-fueled, fuel cell power plant is the complete absence of pollutant emissions and greenhouse gases. This, along with its high fuel efficiency, makes fuel cells an attractive means of power generation. However, even with all of its advantages, fuel cell introduction on a large scale will only become a reality if its cost and durability are competitive with existing technologies. The innovation that is proposed in this project would facilitate these goals by reducing the amount of catalyst material required for efficient operation. H2Systems has projected that by increasing the supply of hydrogen to the stack up to an equivalence ratio of 2 and recycling the anode tail gas, a significant decrease in the size of the reactor could be realized. This would allow for smaller stack designs with less total catalyst mass, and therefore less expense. This would result in a direct saving of up to 25% on anode catalyst material costs alone. We estimate that this initial cost savings amortized over the lifetime of the power plant would result in a reduced power cost of $0.003/-kWh. This saving could be directly transferred to California power consumers.

Figure 1 Initial Picture of Blower Components

This shows the component's size and condition prior to assembly. The white components are composed of Delrin™, fabricated based on drawings generated by H2Systems. The impeller's outside diameter is 53 mm. The black components are ABS, used to hermetically encase the blower. Viton O rings were used throughout. The tubes and fasteners are stainless steel.

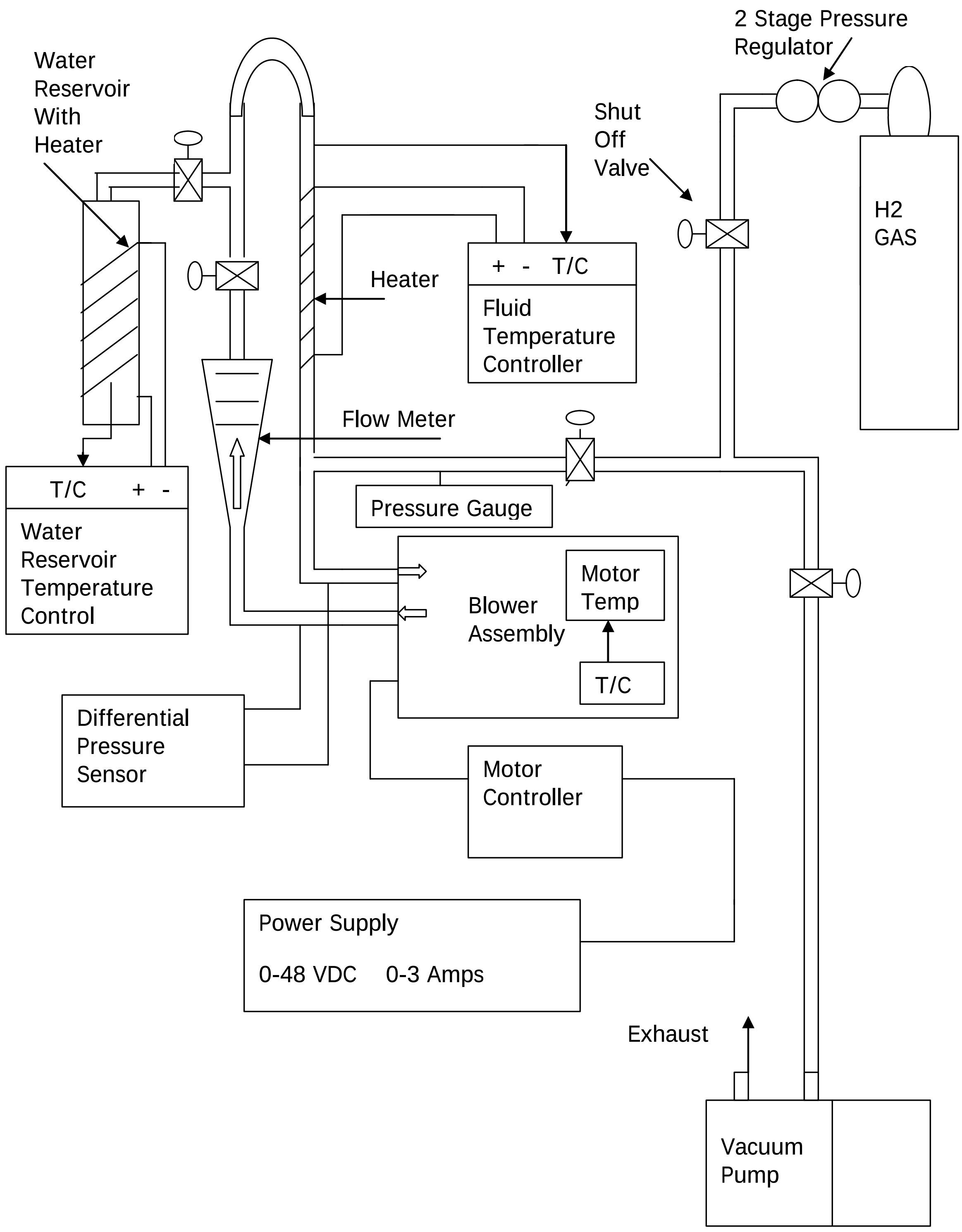

Figure 2 Test Station Schematic

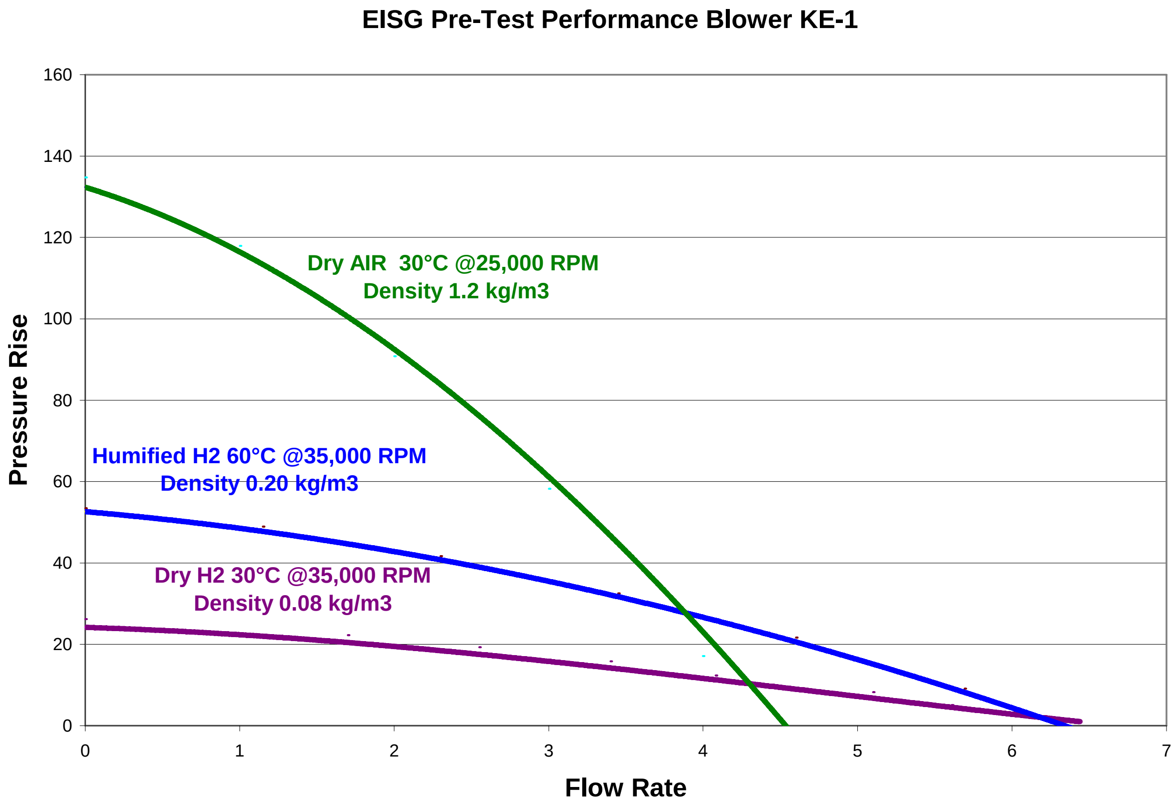

Figure 3 Initial Blower Performance Curves

The pre-test performance of the blower is shown in Figure 3. The results shown are an average of 5 tests. It can be noted from the graph that the flow rates at a given speed are the same for fluids of different densities. It can also be noted that pressure rise for a given speed is proportional to the density of the fluid. These performance curves are the baseline for determining any degradation occurring during the testing program.

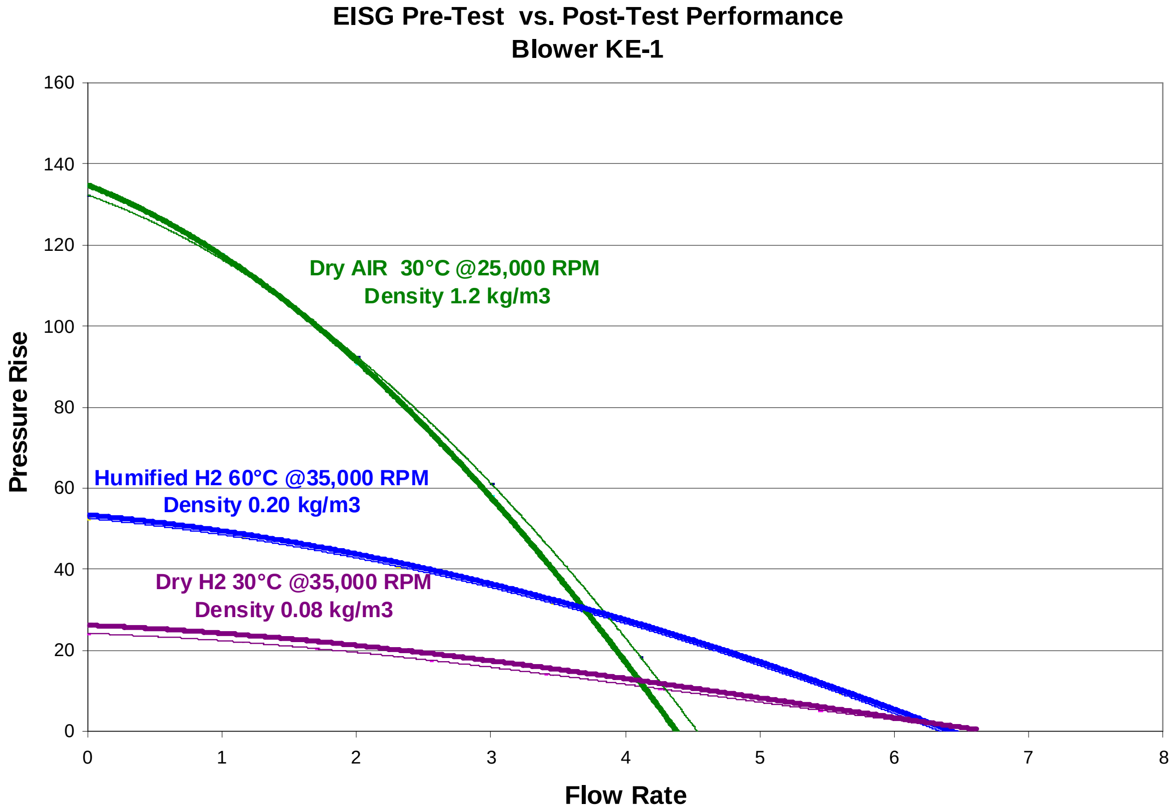

Figure 4 Comparison of Blower Performance Curves

This chart shows the blower performance at the beginning and end of the test program. The fine lines represent the pre-test performance data as was depicted in the previous chart. The broad lines are the data from the post test performance runs. It can be seen that there is virtually no change in the curves, indicating no significant degradation has taken place as a result of the durability testing.

Figure 5 Post-Testing Component Picture

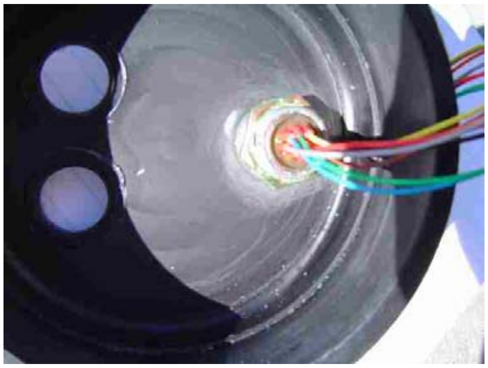

Figure 6 Corrosion of Brass Fixing Nut

Figure 5 shows the condition of the blower components as they were disassembled after completion of post-test evaluation. The dark lines on the impeller, cover, and housing were added prior to assembly to indicate any wear that might have occurred. There was no noticeable change in the components.

Figure 6 shows the corrosion that was found on the nickel-plated brass nut. This emphasizes the need to ensure material compatibility in component selection.

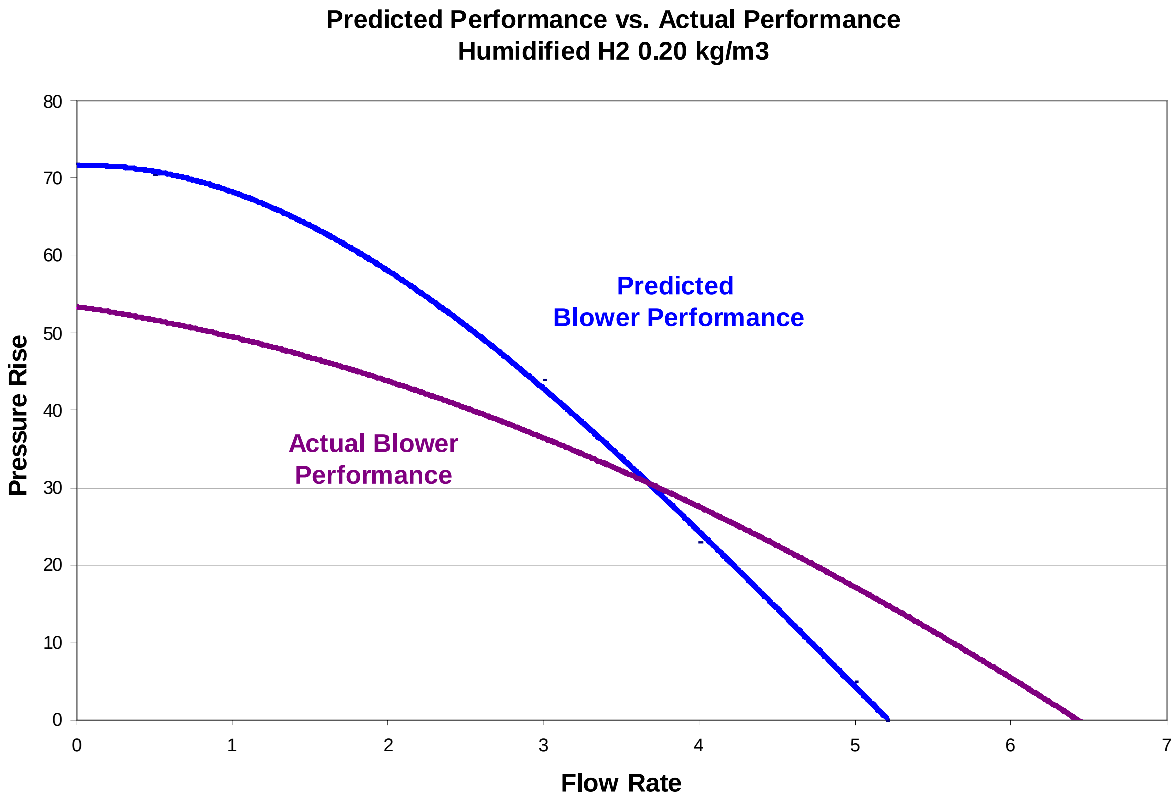

Figure 7 Predicted vs. Actual Performance Curves

Due to inaccuracies in the modeling program, the hardware performance resulted in a higher than expected flow rate with a lower absolute pressure rise. The blower would require minor modifications (a 2mm larger impeller with a 1mm smaller fin radius) to obtain the performance originally predicted. The performance of the actual hardware would be capable of meeting the recirculation requirements of a 1-10kW fuel cell.

Table 1 Cost Summary of Blower in Anticipated Production Volume

Part	Description	Prototype Cost Each	Estimated High Volume Cost Reduction Action	Estimated Hi Vol. Cost
A	3/8" Bulkhead Union	$17.20	High Volume Savings	$10.32
B	Hermetic Panel Receptacle	$35.98	High Volume Savings	$21.59
C	Receptacle Spacer	$1.78	High Volume Savings	$1.07
D	Top Endcap	$86.00	Injection Molded	$17.20
E	Viton O-Ring	$0.13	High Volume Savings	$0.08
F	Casing	$46.00	Injection Molded	$9.20
G	DC Brushless Servomotor (+shaft mod)	$200.00	High Volume Savings	$125.00
H	Tube Connector	$2.00	High Volume Savings	$1.20
J	Viton O-Ring	$0.18	High Volume Savings	$0.11
K	Standard Head Socket Cap Screw	$0.07	High Volume Savings	$0.04
L	Housing	$186.00	Injection Molded	$37.20
M	Viton O-Ring	$0.78	High Volume Savings	$0.47
N	Standard Head Socket Cap Screw	$0.06	High Volume Savings	$0.04
P	Impeller	$208.00	Injection Molded	$41.60
Q	Flat Point Socket Set Screw	$0.14	High Volume Savings	$0.08
R	Cover	$96.00	Injection Molded	$19.20
S	Bottom Endcap	$78.00	Injection Molded	$15.60
T	Vinyl Rod	$0.05	High Volume Savings	$0.03
	TOTAL COST / UNIT	**$941.17**		**$289.70**