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DESIGN OF A RICH INTERNET APPLICATION FOR GAS TURBINE ENGINE SIMULATIONS

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ABSTRACT

Modeling the performance and emissions characteristics of gas turbine engines can involve sequentially solving multiple thermodynamic states of a representative fluid flowing through the engine, evaluating cycle performance, and evaluating the chemical equilibrium of the fluid at select states. The states are defined by the combination of specified thermodynamic conditions, process assumptions derived from established theory of gas turbine engines, and thermodynamic properties of the representative fluid. Internet based applications such as TEST allow experienced analysts to structure and evaluate thermodynamic models of gas turbine engines and separately evaluate the chemical equilibrium of air-fuel mixtures to predict exhaust emissions. Although the TEST thermodynamic and chemical equilibrium data retrieval is automated, analysts are required to first structure the system model.

The Internet based software described in this paper allows analysts to combine the modeling of performance and emissions characteristics of gas turbine engines without the need to first structure a model, broadening the range of potential analysts beyond the thermodynamic and chemical equilibrium communities. The software presented in this work combines a visually rich and Internet based interface to input specifications and display results, a communication mechanism to obtain Internet based thermodynamic and chemical equilibrium data, and a solution architecture to autonomously interpret user inputs and Web based data and model engine parameters. This software also allows analysts to modify the model complexity, accounting for irreversibilities and auxiliary devices such as regenerators, reheaters, and intercoolers as required. Data reduction features such as graphical representation of parametric studies and combustion product distribution are also available within the software.

INTRODUCTION

This paper describes a new Web based, rich internet application (RIA) developed to simulate gas turbine engines. A RIA is an internet browser based program that uses dynamic user interfaces to control client-server communication processes taking place behind the scenes. This RIA is designed to simplify the solution process for gas turbine engine modeling by functioning as a widely accessible and technically accurate application of thermodynamic data.

The RIA is completely Web based, allowing users to access the RIA from multiple locations or computers without the need to install and update any specific software. The RIA is also designed to limit the exposure of complex thermodynamic data to users. The interface only displays relevant input and output parameters. All other data used for thermodynamic modeling is kept behind the scenes, limiting the interface’s complexity.

The solution structure used by the RIA is also kept behind the scenes. Since users only have access and visibility of input and output variables, users are not required to understand the solution structure or thermodynamic relationships required to solve the model, potentially broadening the user base beyond the thermodynamic and chemical equilibrium communities.

PROJECT BACKGROUND

This RIA is grounded in and dependent on Web based thermodynamic and chemical equilibrium data. Without thermodynamic and chemical equilibrium databases available in real time, fast and Web based thermodynamic computations would not be possible. To obtain Web based thermodynamic and chemical equilibrium data, the RIA uses Web services available from The Expert System for Thermodynamics (TEST) [1, 2, 3] developed at San Diego State University.

TEST, among many things, contains applications for users to model generic thermodynamic systems. These applications have the capability to model many thermodynamic devices such as nozzles, diffusers, pumps, evaporators, condensers, compressors, combustors, turbines, and even complete engineering systems such as turbochargers, vapor cycle systems, internal combustion engines and gas turbine engines. However, modeling these devices and systems using generic applications requires that the user possess the knowledge to structure the thermodynamic relationships in order to correctly model the device or system.

Since the gas turbine engine system is not generic and is fully defined, the thermodynamic relationships do not change and are imbedded in the RIA's solution procedure. This embedded structure eliminates the need for a user to understand and input thermodynamic relationships, which reduces the opportunity for structural errors and expands the user base to include those outside of the thermodynamic community.

A similar RIA developed by Mark Patterson at San Diego State University uses this same concept of imbedded solution structure to model thermodynamic and chemical equilibrium behavior of a constant pressure combustion chamber [4]. Patterson's RIA also employs Web Services to compute thermodynamic and chemical equilibrium computations, and then provides tailored information to the user interface. Many of the features developed for Patterson's RIA such as a tabular organization structure, drop down menus, and charts have been incorporated into the gas turbine engine RIA.

Education Applications

Many other computer and Internet based thermodynamic and gas turbine engine simulators currently exist with varying levels of complexity and utility for educational purposes. Teaching gas turbine engine theory is an often in depth process that may begin with first teaching the thermodynamic principles that describe the operation of the various components that a gas turbine engine is comprised of. These components, notably the compressor, combustor, and turbine, are then analyzed together to form a complete thermodynamic cycle, so that overall cycle parameters such as efficiency, power, and back work can be quantified. Depending on the actual engine configuration, other devices such as jet nozzles or recuperative heat exchangers may also be included in the cycle. A particular challenge associated with this method of teaching is that evaluating and analyzing overall cycle performance parameters can be computationally intensive, and consequently time consuming when employing traditional hand calculations. Automating this process through the use of computer based gas turbine engine simulators can significantly reduce the work associated with calculating cycle parameters, affording instructors more time to demonstrate the effects that assumptions and component properties have on the overall cycle performance, furthering a student's understanding of engine cycles.

A computer based gas turbine engine model was developed by Mathidouakis, Politis and Stamatis [5] in 1997, specifically for the purpose of teaching gas turbine engine operation theory. The model allows users to input component parameters using a graphical user interface, rather than input files, for ease of use. Then the component parameters are used by the model to define the engine, and overall cycle performance parameters are calculated. The model has the capability to display cycle performance parameters graphically, so that users can gain a visual understanding of the data's meaning. Changes to the input data can be easily made, allowing for quick analysis of the effects that a device parameter has on the overall cycle performance.

This computer based approach to the teaching of engine cycle operation has also been applied to a broader range of thermodynamic cycles beyond gas turbine engine cycle. In particular, CyclePad [6] was introduced in 1999 by Forbus et al. as an articulate virtual laboratory for constructing and analyzing thermodynamic cycle models. CyclePad incorporates a graphical design environment where users can graphically assemble thermodynamic devices to construct and analyze open and closed cycle systems.

Software such as CyclePad allows users to efficiently design and analyze complex thermodynamic systems, and investigate the consequences that assumptions and device parameters have on overall cycle performance. Incorporating CyclePad into existing thermodynamics course curriculums has been experimented with at the university level, in particular at the United States Naval Academy [7].

While these software packages possess extensive utility by virtue of their ease of data entry and computation power, they are, however, subject to compatibility limitations inherent of all standalone software. Users must have access to computers with the specific operating systems that these software packages are intended to operate with, otherwise an incompatibility may exist. An effective method of mitigating this potential compatibility issue is to design the computer model for use in an Internet browser environment, which can be accessed by all contemporary operating systems. A second advantage to designing the models for use in Internet browsers is that the software can also be accessed across the Internet, eliminating the need for users to download and install the software locally.

One such internet based gas turbine engine model is the Java Gas Turbine Simulator developed by Reed and Afjeh [8] and based on the Java programming language developed by Sun Microsystems Inc. The Java platform allows the software to be accessed across the Internet, broadening its accessibility. This gas turbine simulator is also intended for educational use, including direct use in the classroom.

Design Applications

Even though sophisticated analysis tools such as computational fluid dynamics and finite element analysis are frequently and effectively used to analyze and design gas turbine engine components, traditional thermodynamic cycle analysis remains an important part or gas turbine engine development. Gas turbine engine design, analysis, and optimization practices are still continually influenced by insight gained from thermodynamic cycle analysis.

Haikal and Higazy have presented work [9] on how a new analysis of a gas turbine engine's temperature ratio and pressure ratio can establish many cycle performance characteristics. Among many things, this work shows that a Joule cycle's [10] efficiency is not dependent on the temperature ratio, an insight that may not be readily intuitive, especially given the direct correlation between efficiency and temperature ratio in the limiting Carnot efficiency.

Lewins has presented a thermodynamic analysis [11] of the Joule cycle that reveals a maximum specific work condition. Lewins notes that the maximum efficiency of a Joule cycle is obtained when the pressure ratio is high enough such that the compressor's outlet temperature is equal to the highest temperature that the design will otherwise allow for. In this case, no additional energy is added in the combustion chamber to prevent a further rise in temperature, and the work output of the engine is equal to zero. Lewins also notes that a pressure ratio of unity also produces zero work output, and therefore there must exist a pressure ratio somewhere in between these zero work conditions for which specific work is optimized, and presents a solution for this optimum condition.

Yilmaz has also furthered the thermodynamic cycle analysis of the Joule cycle [12], but rather than designing for maximum specific work or maximum efficiency, he has proposed a new design parameter referred to as the *efficient power criterion*. This criterion is defined as the product of cycle efficiency and power output, and its optimization represents a compromise between maximizing efficiency and maximizing power output.

Guha has presented work that underlines the benefit of including the effects of a real gas in the thermodynamic analysis of gas turbine engine cycles [13], rather than perfect gas treatment. The work reveals that real gas treatment reveals an optimum pressure ratio that maximizes cycle efficiency and is a function of the high temperature, compressor efficiency, and turbine efficiency. This optimum pressure ratio is not revealed under perfect gas treatment where heat capacity is assumed constant.

These examples of gas turbine thermodynamic cycle analyses indicate that thermodynamics is still an effective method of analyzing and improving gas turbine engine design. Many of the insights presented in these examples can be verified by use of the RIA, showing promise that the RIA or similar applications may be of future use to test new hypothesis or new methods of analyzing gas turbine thermodynamic cycles and aid in the advancement of gas turbine engine design.

RIA FUNCTIONALITY

The RIA serves as an intermediary between the user and the thermodynamic data required to model gas turbine engines. The RIA understands user inputs and thermodynamic relationships as they pertain to gas turbine engines, but does not have a local database of property values. To obtain this thermodynamic data, the RIA depends on Web Services [3] to provide this information. The RIA translates this data into relevant output parameters and displays them on the user interface. A flow chart of the communication between the RIA user interface and Web Services is shown in Figure 1.

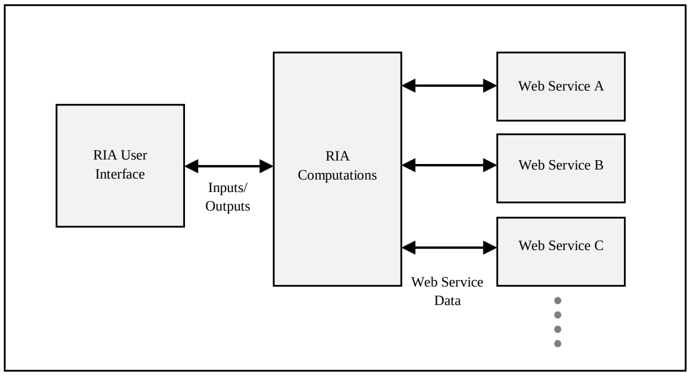


Figure 1. RIA communication flow chart.

The RIA calculates four different engine configurations or models. The models vary in complexity, ranging from the simple model which contains the minimum amount of devices required to define a gas turbine engine, to the complex model which contains a variety of common auxiliary gas turbine engine devices. All of the models are variants of the Brayton cycle, and can be expanded to include irreversibilities represented in the Joule cycle.

The simple model contains only 3 devices; a compressor, a combustor, and a turbine. The fluid flow is analyzed at 4 different flow states.

The regeneration model contains all of the devices from the simple model but also incorporates a regenerator which is a heat exchanger that uses available thermal energy in the exhaust gasses to pre-heat the compressed air entering into the combustor.

The multi-stage model splits the compressor and turbine processes into two separate stages. An intercooler is added between the compressor stages and a re-heater is added between the turbine stages.

The complex model combines all of the devices from the regeneration and multi-stage model and is the most comprehensive model with respect to devices. The complex model device configuration is depicted in Figure 2.

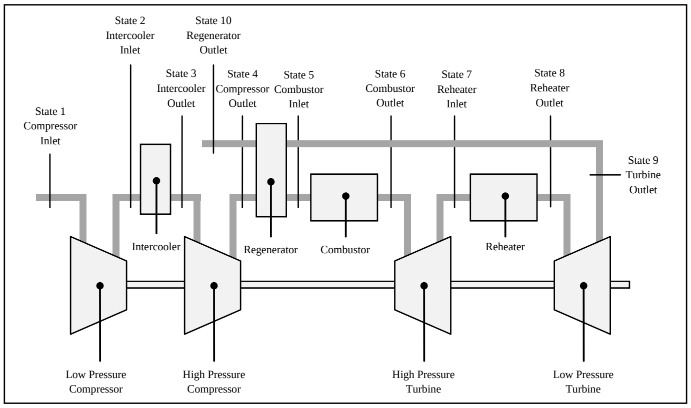
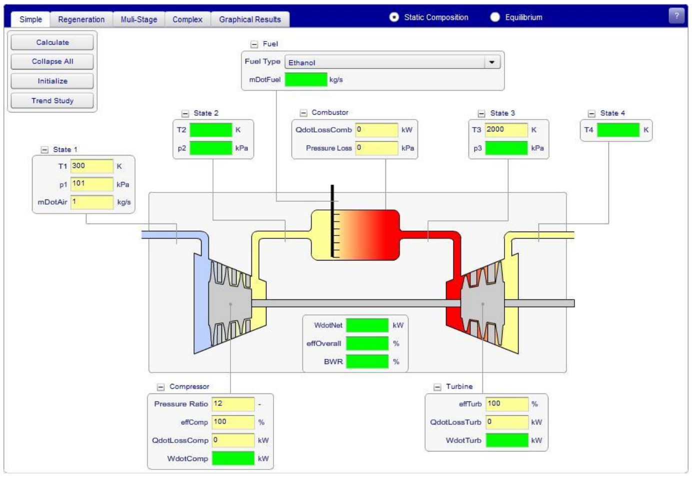


Figure 2. Complex model schematic.

Each model can be computed with two types of solution procedures: static composition or equilibrium composition. With the static composition procedure the fluid flowing through the engine is the same at all states, the effects of added fuel are not included, and combustor outlet temperatures must be specified. The equilibrium solution mode includes the effects of added fuel, and the fluid composition changes based on chemical equilibrium theory [14, 15]. Also, combustor outlet temperatures are calculated directly in this solution mode.

INTERFACE DESIGN

The RIA layout is designed to be clutter free and intuitive. Navigation conventions are adhered to throughout the model, allowing for a consistent look and feel. The interface allows users to show and hide discretionary features thus minimizing the amount of visual complexity while maintaining all of the utility. Access to help pages is also positioned throughout the RIA, allowing users to obtain information on the features or learn more about the capabilities of the RIA. The default user interface is shown in Figure 3.



Fuel
Fuel Type: Ethanol
mDotFuel: 🟩 kg/s

State 1
T1: 300 K
p1: 101 kPa
mDotAir: 1 kg/s

State 2
T2: 🟩 K
p2: 🟩 kPa

Combustor
QdotLossComb: 0 kW
Pressure Loss: 0 kPa

State 3
T3: 2000 K
p3: 🟩 kPa

State 4
T4: 🟩 K

WdotNet: 🟩 kW
effOverall: 🟩 %
BWR: 🟩 %

Compressor
Pressure Ratio: 12 -
effComp: 100 %
QdotLossComp: 0 kW
WdotComp: 🟩 kW

Turbine
effTurb: 100 %
QdotLossTurb: 0 kW
WdotTurb: 🟩 kW

Figure 3. Default user interface.

The interface is organized so that users can switch back and forth between models, comparing results without losing any data, and users can also easily switch between static composition and equilibrium solution modes at any time. The four engine models each placed in separate tabs in the RIA and are accessed by selecting the corresponding tab on the tab bar. The tab bar is located at the top of the interface and remains stationary throughout navigation. When a particular tab is selected, its color changes slightly to distinguish it from the others, indicating which engine model is being accessed.

The tab bar also includes a tab labeled “Graphical Results”. This tab is reserved for displaying any available graphical data that is generated in other portions of the RIA. Graphical data includes trend study plots that are generated from any of the models while in static composition mode, and combustion products charts that are generated while in equilibrium mode. The two solution modes can be toggled by selecting the desired mode from the radio buttons located next to the tab bar.

Help pages, embedded throughout the RIA, are designed to provide the user with specific information about using the RIA. Help pages can be accessed by selecting help buttons labeled “?”. These help buttons are located at the top right hand corner of the RIA or sub-window. The help topics provide the user with information about the model, trend study setup, or graphical results that the user is currently working with, and are context sensitive. Selecting the help button when the regeneration model tab is selected will provide information specific to the regeneration model, whereas selecting the help button when the complex model tab is selected will provide information specific to the complex model.

Properties that are specifically tied to a flow state or device are visually tied to that respective flow state or device. This visual linking of the data with the engine model schematic helps the user to understand the source and relevance of the data. The data is linked by graphical strings that connect the property panel to its respective flow state or device.

If a specific property panel is not important to the user, it can be minimized or collapsed by clicking the “-“ button next to the flow state or device label. This will visually hide the property panel and reduce the complexity of the interface. The property panel can be accessed at any time by clicking the “+” button next to the flow state or device label.

WEB SERVICES

The RIA understands the relationships between thermodynamic properties as they pertain to gas turbine engines, but does not have a database of actual values. The user inputs supply the RIA with some information to define the gas turbine engine model, and the RIA uses Web Services to retrieve all other unknown thermodynamic properties. Thermodynamic parameters such as pressure, temperature, enthalpy and entropy are sent to and retrieved from various Web Services.

These properties are evaluated at various states along the gas turbine engine flow path. Web Service requests for thermodynamic properties of a flow state must include definition of the flow composition, and two known thermodynamic flow properties at that state. The Web Service will process that information, compute other thermodynamic properties, and return requested property values to the RIA. Each flow state for the complex model is plotted on a temperature-entropy diagram shown in Figure 4.

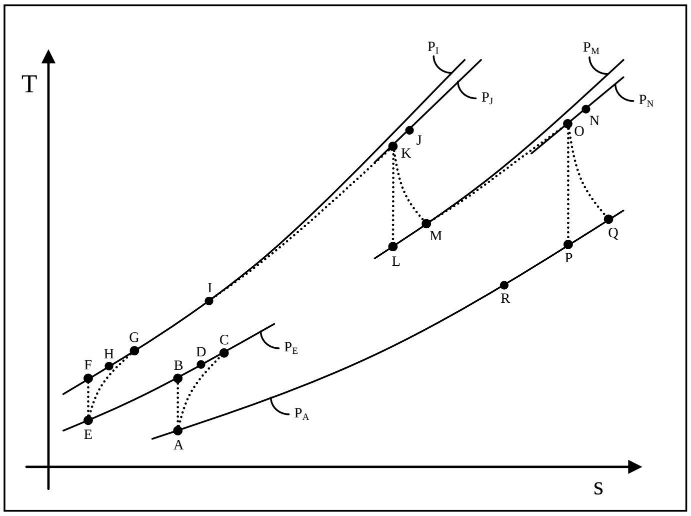


Figure 4. Complex model T-s diagram.

The flow composition (fluid mixture) is defined by a list of comprising chemical species and their respective quantities. Since the mixture represents a flow state, only the relative size of each species is regarded. Each species is supplied to the Web Service in Simplified Molecular Input Line Entry System (SMILES) notation [16]. The species' SMILES is combined with its respective quantity and packaged into a Java Script Object Notation (JSON) text string [17]. An example of a mixture composed of 1 kg of oxygen and 1 kg of nitrogen is shown below in JSON format.

{"O=O":{"kg":1},"[H][H]":{"kg":1}}

JSON strings such as this are sent to the Web Services along with 2 thermodynamic properties and the other thermodynamic properties are returned to the RIA, also in JSON format, where they are then decoded and used in local computations based on thermodynamic relationships.

DATA ANALYSIS

The output data is not just limited to the pairing of parameters with calculated values. The RIA is also designed to make this data easy to analyze. Trend studies allow a user to plot the relationships between variables and visually identify trends and optimizations. Combustion product displays allow a user to quickly see how design changes can affect gas turbine engine emissions.

Trend studies involve running an engine simulation multiple times, each time changing a certain variable by a set amount while keeping all other variables constant. The results for each solution are collected for comparison. This allows the user to analyze the effects that changing a single variable can have on the overall cycle. The RIA will plot the results so that users can view the trends of output variables. A trend study results page is shown in Figure 5.

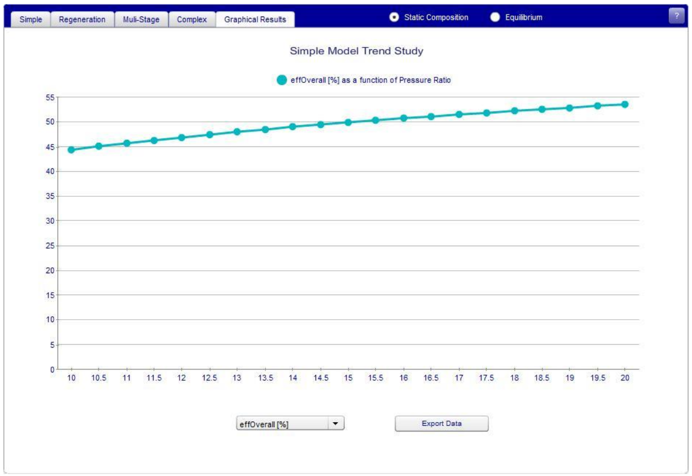


Figure 5. Trend study results page.

If the user would like to plot another output variable as a function of the same trend variable, then the new output variable can simply be selected from the drop down menu below the graph. When a new output variable is selected the graph and legend are automatically updated.

All of the trend study data is available to be exported for use outside of the RIA. Selecting an "Export Data" button below the graph will open a data window containing all of the trend study data presented in comma separated value (CSV) format.

When the RIA is set to the equilibrium mode, products of combustion are calculated by a chemical equilibrium Web Service. The RIA uses these products as the fluid composition for succeeding calculations and also makes the product composition data available for display. The products can be viewed in terms of mass fractions or mole fractions by selecting one of the radio buttons at the top of the products display page. The species which are small (less than 0.01% of the mixture) in regard to either mass or mole fraction are grouped together as "trace" species. The distribution of trace species is given shown in a second pie chart. The products display page is shown in Figure 6.

Figure 6. Products display page.

RESULTS COMPARISONS

To verify that the RIA is calculating output parameters correctly, a comprehensive set of thermodynamic results have been compared to results obtained from the TEST generic thermodynamic applications. These TEST applications were first structured to mirror the exact function of the various RIA models, and then the output results were compared to data obtained from the RIA. These thermodynamic data comparisons were made by varying input parameters such as pressure ratio or turbine efficiency over a range of values. The regenerator and multi-stage models were used to verify that their specific input parameters such as regenerator and intercooler effectiveness function correctly.

The simple model was used to validate that input parameters such as pressure ratio and compressor efficiency are structured correctly. A standard set of constants were used to define the simple model in the RIA as well as TEST. The other selected parameters were then varied, one at a time, and output parameters such as cycle efficiency, back work ratio, net work output, and state temperatures were charted to verify correlation with TEST data. A cycle efficiency and work results comparison to TEST data is given in Figure 7.

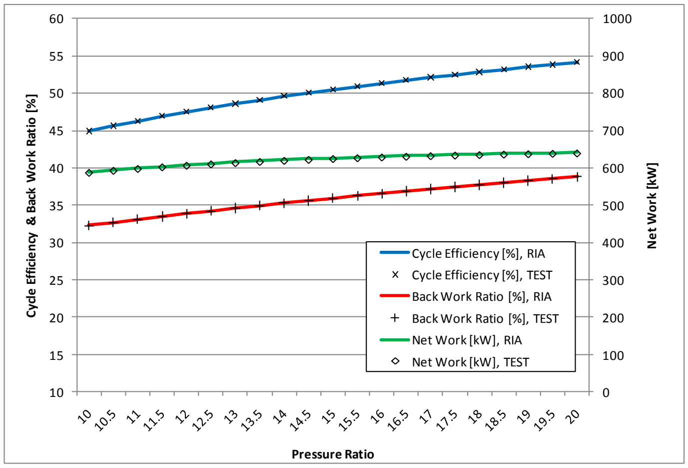


Figure 7. Efficiency and work results comparison for changes in pressure ratio.

The compressor efficiency was varied from 50% to 100%. A cycle efficiency and work results comparison to TEST data is given in Figure 8.

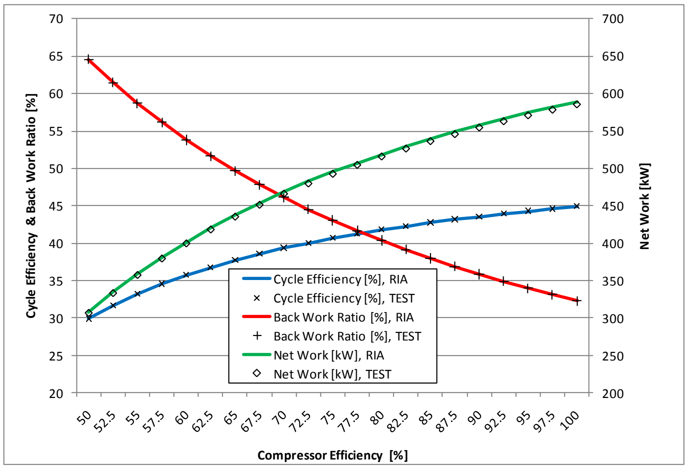


Figure 8. Efficiency and work results comparison for changes in compressor efficiency.

Modeling the equilibrium mode in TEST could not be done because an analogous TEST application is not readily available. The equilibrium results were, however, compared to the ideal conditions which are easily modeled by the simple model in static composition mode. Relevant equilibrium parameters are compared to the ideal static composition values to verify that the parameters do not exceed or diverge from ideal values.

Cycle efficiency and fuel consumption results were compared to the ideal static composition mode. The pressure ratio was varied from 10 to 20 for each comparison. The cycle efficiency and fuel consumption results comparisons for acetylene is shown in Figure 9. In all cases tested the ideal conditions (static analysis) were shown to consume less fuel and operate more efficiently than the more realistic equilibrium results.

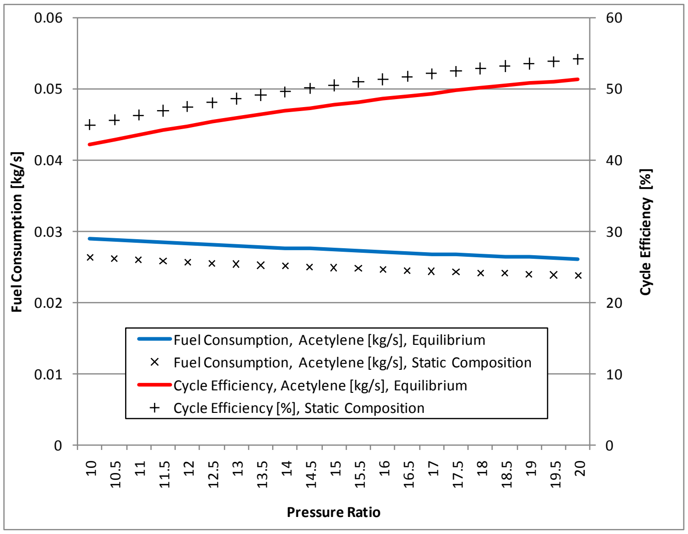


Figure 9. Comparison of equilibrium results to static composition with acetylene fuel.

CONCLUSION

Although the main components that comprise this RIA are not new, their integration is believed to be novel and useful. This RIA was developed to combine a graphical environment for gas turbine engine cycle thermodynamic solutions with the capability to analyze exhaust emissions based on chemical equilibrium theory.

The approach was to develop these RIA features for use in a web environment where they can accessed from anywhere with internet access, maximizing its availability. The RIA user interface is intended for users with limited understanding of thermodynamic or chemical equilibrium principles. The architecture allows for the RIA to be accessed from anywhere through the internet, only requiring minimum local software to operate. All thermodynamic and equilibrium calculations are performed remotely by Web Services that provide data behind the scenes.

The RIA engine models have dynamic complexity, allowing users to account for irreversibilities and auxiliary devices such as regenerators, reheaters, and intercoolers as desired. Data reduction features such as graphical representation of parametric studies and combustion product distribution are also available within the software.

The these features and capabilities integrated into the RIA are intended to be of use in the educational environment, allowing students to interact with the RIA and develop an understanding of cause-effect relationships between thermodynamic and chemical equilibrium parameters as they pertain to gas turbine engine cycles.

ACKNOWLEDGMENTS

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