Energy and Exergy Analysis of a University Power Plant

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ABSTRACT

Data acquisition systems present in university power plants can be used to carry out educational and research studies. This paper presents a method to utilize real-time data from a university power plant to carry out thermodynamic studies. The study presented here involves application of the first and second laws of thermodynamics to the powerhouse components of the plant. The computer program developed is a heat balance program based on energy and exergy principles. The heat balance increases our understanding of power plant performance. The program also calculates plant emissions which are useful for reporting to state and federal regulatory agencies. The program has many additional features like trending real-time and historic data.

Introduction

The University of Massachusetts has a Combined Heat and Power (CHP) plant to produce steam and electricity for the campus. The plant has a 16.5 MW electric capacity and a 475,000 lbs/hr steam capacity. The electricity is produced by one 10 MW gas turbine, one 2.5 MW high pressure steam turbine and one 4 MW low pressure steam turbine. The steam is produced by one 100,000 lbs/hr heat recovery steam generator (HRSG), one 125,000 lbs/hr high pressure steam boiler and two 125,000 lbs/hr low pressure steam boilers. The gas turbine and boilers are capable of operating on natural gas and #2 fuel oil. The HRSG has a duct burner which can fire natural gas only. Steam is supplied to the university campus in two separate lines; a high pressure line at 200 psig for the outer peripheries of the campus and a low pressure line at 20 psig for the inner campus.

The plant has a state-of-the-art Supervisory Control and Data Acquisition (SCADA) system. Real-time data from several thousand field instruments is being acquired by Rockwell Automation's RSLinx™ OPC (Object Linking and Embedding for Process Control) server. The OPC server fulfils two purposes. Firstly, it streams the real-time data to the plant controller's computer (also called HMI or Human Machine Interface) for supervisory control purposes (Putman 2004). Second, it sends the data at regular intervals to a Microsoft® SQL Server™ (also called 'Historian') for long-term archiving. The data from only 675 key instruments is sent to the Historian.

Recently, we here at the Center for Energy Efficiency and Renewable Energy (CEERE) laboratory, collaborated with the power plant department and setup a computer with a network connection to the plant Historian. Over the last two decades MATLAB® has become the most widely used computing platform in academia. It has excellent documentation and is very easy to learn by students and develop new applications. Hence, at our end we decided to use MATLAB® as the software to import plant data and perform further analysis. The importing of data is made possible by the Database Toolbox™ of MATLAB®. We were unable to get permission to directly connect to the OPC server from MATLAB® using the OPC Toolbox™. As the OPC server sends data to the Historian in real-time, our program operates continuously to read the latest data from the Historian, in effect creating a real-time data acquisition system at our end.

MATLAB® has two interesting feature called the Graphical User Interface Development Environment (GUIDE®) and MATLAB® Compiler Runtime (MCR®). The GUIDE® feature has been used to develop a GUI program to display the heat balance program (Smith 2006). The MCR® feature packages the heat balance program into a stand-alone Microsoft® Windows™ application which can be run on machines not having MATLAB®. The idea is to install the heat balance program on a computer in the power plant's control room at some time in the near future. In addition to displaying the results, we also write them to an OPC simulation server installed on our local machine. The simulation server is provided by Iconics, Inc. Writing the data to the simulation server allows us to use the *trend* function available in the OPC Toolbox™ to trend calculated results in real-time. Figure 1 shows the main GUI screen for the plant where several system variables are being displayed in real-time. From this screen a user can navigate to view operations of individual components and also perform useful tasks like trending real-time data, viewing historical data and printing energy and emissions reports.

Power plant thermodynamic studies involve two major approaches; the energy method and the exergy method. The energy method involves application of the first law of thermodynamics alone, whereas the exergy method involves the combined application of the first and second laws of thermodynamics (Bejan 1988). The relevant equations of both methods are applied here to individual powerhouse components to calculate various performance parameters like combustion efficiency, isentropic efficiency, heat transfer efficiency, emission levels and entropy generation rates.

Energy Analysis

Energy analysis involves the application of the first law of thermodynamics to each powerhouse component (Cengel and Boles 1993). From the first law point of view, the prime variables of interest in the gas turbine and boiler calculations are their combustion efficiencies, in the HRSG calculations the heat transfer efficiency and in the steam turbine calculations their isentropic efficiencies.

The thermodynamic performance of the plant is indicated by the plant figure of merit (*FOM*). *FOM* is defined as the sum of all useful energy output divided by the sum of all fuel energy input. The *FOM* for this plant is given by Equation (1), where P_{total} is the total power output, m_{HPS} is the total high pressure steam output, h_{HPS} is the enthalpy of the high pressure steam, m_{LPS} is the total low pressure steam output, h_{LPS} is the low pressure steam enthalpy, m_{fw} is the total feedwater input, h_{fw} is the feedwater enthalpy, $m_{plant\ gas}$ is the total plant natural gas consumption, e_{gas} is the energy content of gas, $m_{plant\ oil}$ is the total plant oil consumption and e_{oil} is the energy content of oil. The *FOM* for this plant is in the range of 75% to 80% at all times.

$$FOM = \frac{P_{total} + m_{HPS}h_{HPS} + m_{LPS}h_{LPS} - m_{fw}h_{fw}}{m_{plant\ gas}e_{gas} + m_{plant\ oil}e_{oil}} \qquad (1)$$

The calculations carried out and results obtained for all components are quite exhaustive and impractical to present in a single paper. Hence, in order to give an overview, the calculations of the HRSG are presented. Figure 2 shows the results of the calculations described in Table 1 to 4 being displayed in real-time, along with a schematic and an energy-temperature diagram. The numeral subscripts of the item notations in Table 1 to 4 are indicated in these two diagrams. Equation (2) is the chemical equation of the combustion occurring in the HRSG [3].

$$aCO_2 + bH_2O + cO_2 + dN_2 + eSO_2 + fCH_4 + gNH_4OH \rightarrow xCO_2 + yH_2O + zO_2 + uN_2 + v\left(NO + NO_2\right) + wSO_2 \quad (2)$$

The mole flow rates *a*, *b*, *c*, *d, e*, *f* and *g* of the reactants can be calculated by the formulae given in Table 5. The mole flow rates *z* and *v* of the two of the products can be calculated from measured data and the formulae given in Table 6. Mole balancing of C, H, S, O and N in Equation (2) gives Equation (3), from which the mole flow rates *x*, *y*, *u* and *w* of the products are calculated. Table 7 gives the formulae to calculate the emissions and the results are displayed and trended along with other HRSG results seen in Figure 2.

$$C : a + f = x \Rightarrow x = a + f \quad (3a)$$

$$H : 2b + 4f + 5g = 2y \Rightarrow y = \frac{2b + 4f + 5g}{2} \quad (3b)$$

$$N : 2d + g = 2u + 2v \Rightarrow u = \frac{2d + g - 2v}{2} \quad (3c)$$

$$S : e = w \Rightarrow w = e \quad (3d)$$

Figure 3 shows an example of real-time trends. The inlet and outlet pressures and temperatures of the high pressure steam turbine are being trended in the screen.

Exergy Analysis

Exergy analysis involves the combined application of the first and second laws of thermodynamics. In exergy analysis the same set of equations is applicable to all powerhouse components, disregarding the differences in the internal thermodynamic cycle of the components. This approach provides a common scale to compare performances of components which are thermodynamically different in nature. Equation (4) is the set of exergy equations for open systems (Bejan 1988).

$$\frac{dE}{dt} = \sum_{i=0}^{n} \dot{Q}_i - \dot{W} + \sum_{in} \dot{m}h - \sum_{out} \dot{m}h \quad (4a)$$

$$\dot{S}_{gen} = \frac{dS}{dt} - \sum_{i=0}^{n} \frac{\dot{Q}_i}{T_i} - \sum_{in} \dot{m}s + \sum_{out} \dot{m}s \geq 0 \quad (4b)$$

The entropy generation and heat lost to the atmosphere are the prime variables of interest to be calculated for all components using Equation (4). The entropy generation is directly proportional to the exergy destruction. All variables in Equation (4), for all components, are available as either directly measured data or calculated data from the first law analysis. Figure 4 shows the calculations of the exergy analysis being displayed in real-time. On an average, the gas turbine is accountable for destroying of 40% of the plant exergy. The steam turbines destroy the least exergy since they are non-combustion powerhouse components.

Conclusion

Data acquisition systems present in university power plants can be effectively used to carry out educational and research studies. The thermodynamic performance monitoring study presented here increases our knowledge about the performance of the plant's powerhouse components and the plant as a whole. The study bridges the gap between textbook knowledge and the real world. The work described in this paper is an on-going graduate research project. Students working in the Industrial Assessment center (IAC) program at the university are carrying out these analyses for their master's and PhD theses. The work will also address topics on plant emission reporting and regulations in the near future.

Acknowledgement

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References

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Appendix

Table 1. HRSG Measured Data

Notation	Item	Units
m_{gas}	Gas Flow	lbs/hr
m_{fw}	Feedwater Flow	lbs/hr
m_{steam}	Steam Flow	lbs/hr
P_{drum}	Drum Presssure	psig
T_2	Air-Side Superheater Outlet Temperature	DegF
P_8	Steam-Side Superheater Outlet Pressure	psig
T_8	Steam-Side Superheater Outlet Temperature	DegF
T_4	Air-Side Economizer Outlet Temperature	DegF
m_{NH4OH}	Aqueous Ammonia Flow	scfm
$m_{exhaust\ NOx}$	NO_x Emission	ppm (mg/kg)
$m_{exhaust\ O2}$	O_2 Emission	% of Exhaust

Table 2. HRSG Assumed Data

Notation	Item	Value	Units
m_{CO2}	CO_2 Flow	$m_{gas\ turbine\ exhaust\ CO2}$	kg/s
m_{H2O}	H_2O Flow	$m_{gas\ turbine\ exhaust\ H2O}$	kg/s
m_{O2}	O_2 Flow	$m_{gas\ turbine\ exhaust\ O2}$	kg/s
m_{N2}	N_2 Flow	$m_{gas\ turbine\ exhaust\ N2}$	kg/s
m_{SO2}	SO_2 Flow	$m_{gas\ turbine\ exhaust\ SO2}$	kg/s
T_1	Air-Side Superheater Inlet Temperature	$T_{gas\ turbine\ exhaust}$	DegC
T_5	Feedwater Temperature	228.0	DegC
T_{PP}	Pinch Point Temperature	10.0	DegC
T_{std}	Standard Temperature	15.0	DegC
P_{atm}	Atmospheric Pressure	101.325	kPa
c_1	Conversion Constant	60.0	sec/min
c_2	Conversion Constant	60.0	min/hr
c_3	Conversion Constant	0.45	kg/lb
c_4	Conversion Constant	6.89	kPa/psi
c_5	Conversion Constant	0.03	m^3/ft^3
MW_{CH4}	Natural Gas (CH_4) Molecular Weight	16.04	kg/kmol
MW_{CO2}	Carbon Dioxide Molecular Weight	44.01	kg/kmol
MW_{H2O}	Water Vapor Molecular Weight	18.02	kg/kmol
MW_{O2}	Oxygen Molecular Weight	31.99	kg/kmol
MW_{N2}	Nitrogen Molecular Weight	28.01	kg/kmol
MW_{SO2}	Sulfur Dioxide Molecular Weight	64.06	kg/kmol
MW_{NH4OH}	Aqueous Ammonia Molecular Weight	35.04	kg/kmol
MW_{NOx}	NO_x (NO+NO2) Molecular Weight	76.01	kg/kmol
R_{NH4OH}	Aqueous Ammonia Ideal Gas Constant	0.237	kJ/(kg.K)

Table 3. Standardization of HRSG Measured Data to SI Units

Notation	Item	Conversion Formula	Old Units	New Units
m_{gas}	Gas Flow	$m_{gas} = \frac{m_{gas} \times c_3}{c_1 \times c_2}$	lbs/hr	kg/s
m_{fw}	Feedwater Flow	$m_{fw} = \frac{m_{fw} \times c_3}{c_1 \times c_2}$	lbs/hr	kg/s
m_{steam}	Steam Flow	$m_{steam} = \frac{m_{steam} \times c_3}{c_1 \times c_2}$	lbs/hr	kg/s
P_{drum}	Drum Presssure	$P_{drum} = \left(P_{drum} + 14.5\right) \times c_4$	psig	kPa
T_2	Air-Side Superheater Outlet Temperature	$T_2 = \frac{5}{9}\left(T_2 - 32\right)$	DegF	DegC
P_8	Steam-Side Superheater Outlet Pressure	$P_8 = \left(P_8 + 14.5\right) \times c_4$	psig	kPa
T_8	Steam-Side Superheater Outlet Temperature	$T_8 = \frac{5}{9}\left(T_8 - 32\right)$	DegF	DegC
T_4	Air-Side Economizer Outlet Temperature	$T_4 = \frac{5}{9}\left(T_4 - 32\right)$	DegF	DegC
m_{NH4OH}	Aqueous Ammonia Flow	$m_{NH4OH} = \frac{m_{NH4OH} \times c_5}{c_1} \times \frac{P_{std}}{R_{NH4OH}\left(T_{std} + 273.15\right)}$	scfm	kg/s

Table 4. HRSG Calculated Data

Notation	Item	Formula	Units
m_{air}	Air Flow	$m_{air} = m_{CO2} + m_{H2O} + m_{O2} + m_{N2} + m_{SO2}$	kg/s
m_{spray}	Spray Water Flow	$m_{spray} = m_{steam} - m_{fw}$	kg/s
T_{drum}	Drum Temperature	From Steam Tables corresponding to P_{drum}	DegC
T_3	Air-Side Evaporator Outlet Temperature	$T_3 = T_{drum} + T_{PP}$	DegC
h_1	Air-Side Superheater Inlet Enthalpy	From Ideal Gas Properties of Air Tables corresponding to T_1	kJ/kg
h_8	Steam-Side Superheater Outlet Enthalpy	From Steam Tables corresponding to P_8 and T_8	kJ/kg
h_5	Feedwater Enthalpy	From Steam Tables corresponding to P_8 and T_5	kJ/kg
$\eta_{overall}$	Overall Efficiency	$\eta_{overall} = \frac{m_{steam} \times (h_8 - h_5)}{m_{air} \times h_1 + m_{gas} \times e_{gas}}$	Dimensionless
m_{exh}	Exhaust Flow	$m_{exh} = m_{air} + m_{gas} + m_{NH4OH}$	kg/s

Table 5. HRSG Mole Flow Rate of Reactants

Notation	Item	Formula	Units
a	CO_2 Mole Flow Rate	$a = \frac{m_{CO2}}{MW_{CO2}}$	kmol/s
b	H_2O Mole Flow Rate	$b = \frac{m_{H2O}}{MW_{H2O}}$	kmol/s
c	O_2 Mole Flow Rate	$c = \frac{m_{O2}}{MW_{O2}}$	kmol/s
d	N_2 Mole Flow Rate	$d = \frac{m_{N2}}{MW_{N2}}$	kmol/s
e	SO_2 Mole Flow Rate	$e = \frac{m_{SO2}}{MW_{SO2}}$	kmol/s
f	CH_4 Mole Flow Rate	$f = \frac{m_{gas}}{MW_{CH4}}$	kmol/s
g	NH_4OH Mole Flow Rate	$g = \frac{m_{NH4OH}}{MW_{NH4OH}}$	kmol/s

Table 6. HRSG Mole Flow Rate of Products

Notation	Item	Formula	Units
z	O_2 Mole Flow Rate	$z = \frac{m_{exhaust\ O2} \times m_{exh}}{100 \times MW_{CO2}}$	kmol/s
v	NO_x Mole Flow Rate	$v = \frac{m_{exhaust\ NOx} \times m_{exh}}{10^6 \times MW_{NOx}}$	kmol/s

Table 7. HRSG Mass Flow Rates of Products

Notation	Item	Formula	Units
m_{CO2}	CO_2 Emission	$m_{CO2} = MW_{CO2} \times x$	kg/s
m_{H2O}	H_2O Emission	$m_{H2O} = MW_{H2O} \times y$	kg/s
m_{O2}	O_2 Emission	$m_{O2} = MW_{O2} \times z$	kg/s
m_{N2}	N_2 Emission	$m_{N2} = MW_{N2} \times u$	kg/s
m_{NOx}	NO_x Emission	$m_{NOx} = MW_{NOx} \times v \times 10^6$	mg/s
m_{SO2}	SO_2 Emission	$m_{SO2} = MW_{SO2} \times w$	kg/s

Figure 1. Plant Screen

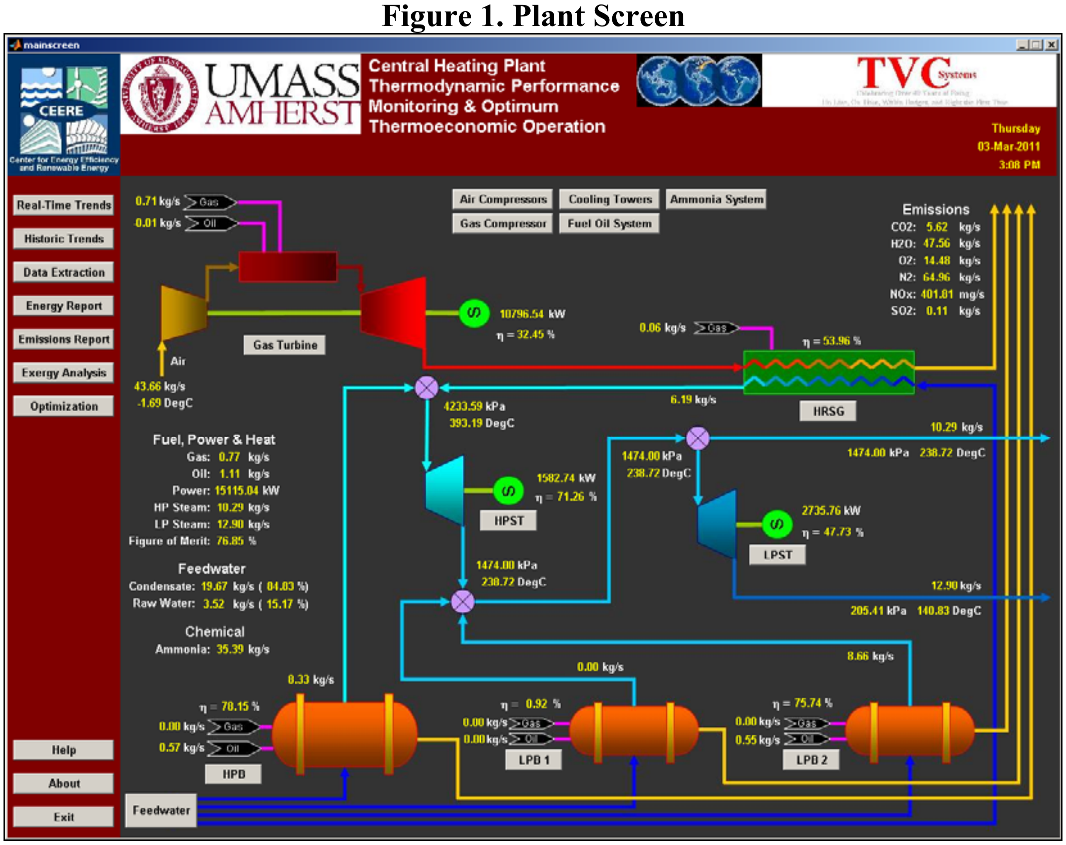

Figure 2. HRSG Screen

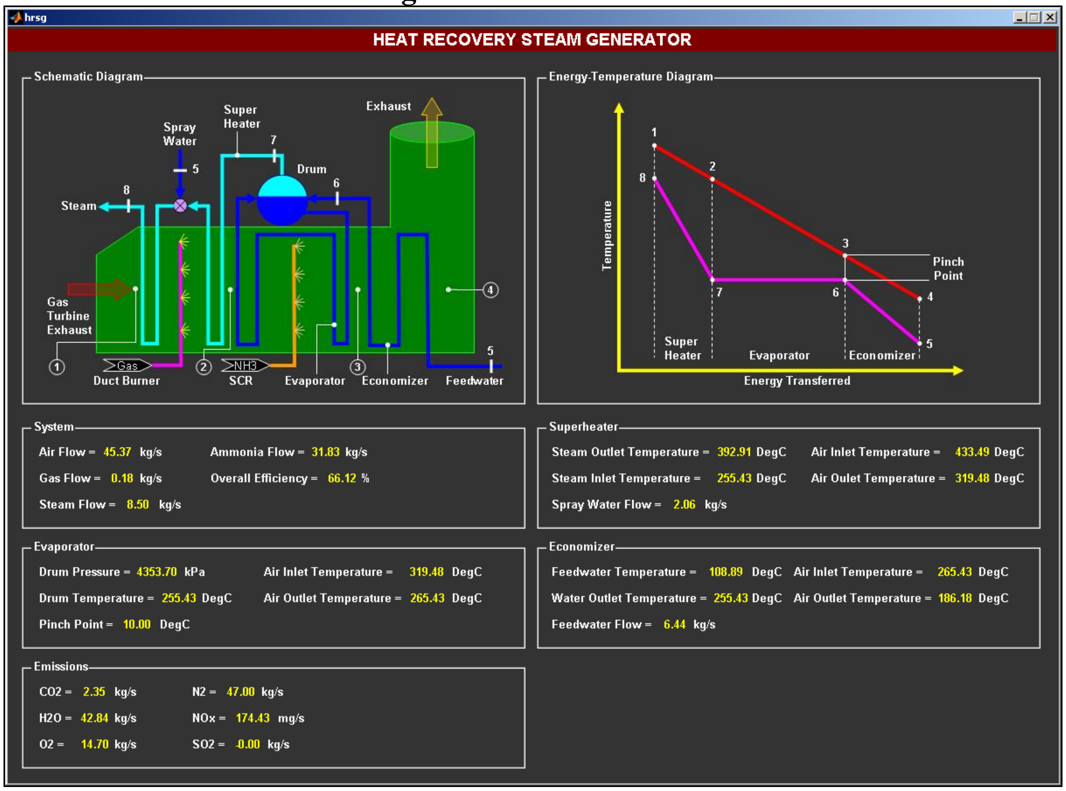

Figure 3. Real-Time Trends Screen

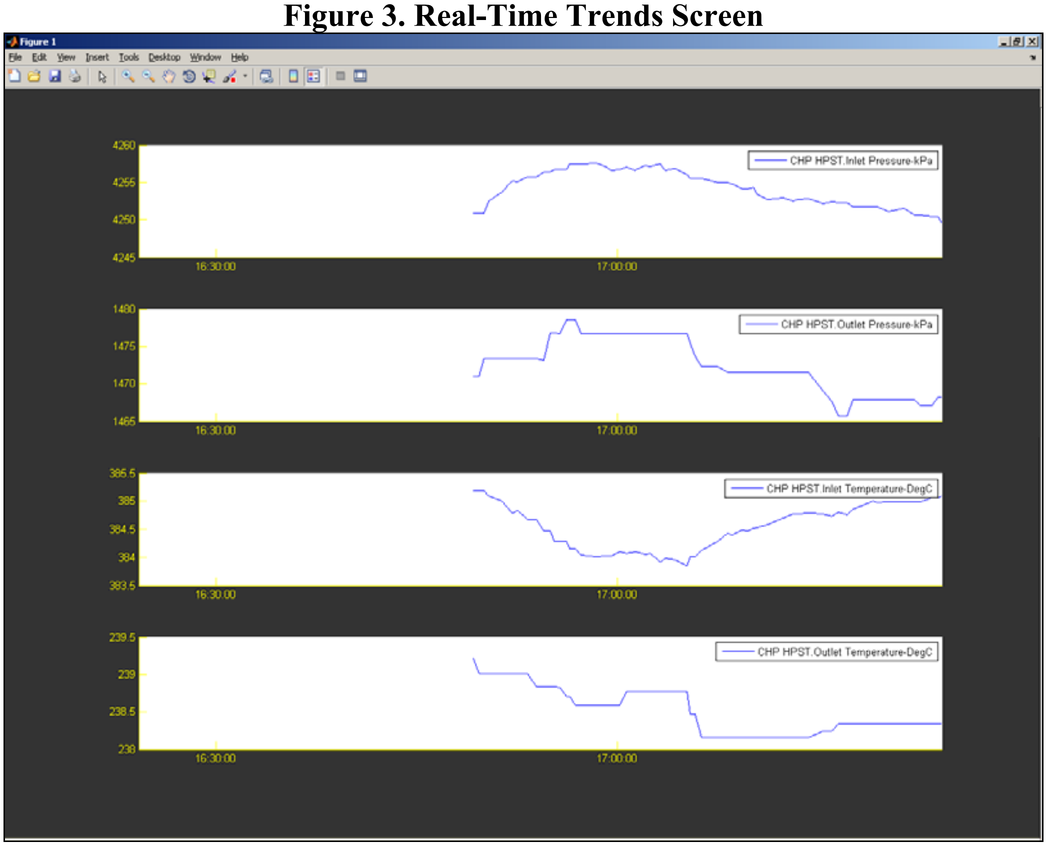

Figure 4. Exergy Analysis Screen