Session Number:

A Comprehensive Energy Model Development for Off-Highway Vehicles

Ayhan Zora*, Mohammed F. Fahmy, Recayi Pecen, Faruk Taban**

Department of Industrial Technology, University of Northern Iowa, Cedar Falls, Iowa/
(*) Technology Center, Deere & Company, Moline, Illinois/
(**) Department of Mechanical Engineering, University of Nevada, Reno, Nevada

Abstract

Utilizing machine and thermal system simulations (vehicle energy models) can be very helpful for vehicle manufacturing companies to develop a machine with acceptable component temperatures, less heat loads to the vehicle cooling systems, and reduced emissions that will also reduce the overall product development cycle. Energy models of vehicles were developed mostly in the automotive industry, and most of these studies in the past were based on partial energy models.

The objective of this study is to create a comprehensive energy model for agricultural machinery by using EASY5, which will be a basis for future work on similar products and a subject of advanced modeling and simulation classes in engineering technology institutions. A tractor model from a Midwest off-road machinery manufacturing company was selected as a starting point for modeling. The work in creating the model has been presented in detail. Verification of the simulation model was carried out using the results from three different wind tunnel tests that were conducted by the Midwest Company; namely the PTO test, the AXLE test, and the high-speed wind tunnel transport test. The critical parameters were selected to be analyzed for each test were the top tank temperature, the intake manifold temperature, the oil cooler inlet temperature, the oil cooler outlet temperature, the fuel cooler inlet temperature, the fuel cooler outlet temperature, the fan speed, the engine speed, the PTO torque and the axle torque. Most of the electrical and mechanical engineering and technology curricula include instrumentation, advanced CAD, and control courses using AutoCAD and LabView™ combined with a variety of instrumentation inputs from proximity sensors and other transducers provided a good learning tools for undergraduate and graduate students. This comprehensive energy model promises to be included in an elective undergraduate senior and graduate level advanced simulation and data acquisition classes.

I. Introduction

The off-highway sector has been under increasing pressure to lessen operating costs and emissions. The main reason of the pressure stems from the regulation of the U.S. Environmental Protection Agency (EPA). In 1990 amendments to the Clean Air Act authorized the EPA to regulate off-highway diesel engine emissions for new engines. Recognizing the need for the off-highway vehicle industry, the Society of Automotive Industry and U.S. Department of Energy

(DOE) organized a joint meeting to determine critical research and development areas for minimizing off-highway vehicle emissions while improving system performance [1].

Companies are expected to run numerous tests on prototypes to validate their products before selling them to customers. "In general, prototype testing is an expensive tool for design as there are many applicable component configurations as well as a large number of physical variables that need to be measured during testing and validation" [2]. Ability to predict heat loads and critical temperatures without conducting expensive and time-consuming prototype tests can help companies to reduce cost and to be more competitive. Therefore a comprehensive energy simulation model, which has the ability to predict heat loads and critical temperatures in off-highway vehicles, can be a useful tool for vehicle manufacturing companies in the competitive market.

II. An overview on EASY5

EASY5 is a graphics-based software tool used to model, simulate, and design dynamic systems characterized by differential, difference, and algebraic equations [3]. Boeing Inc. originally developed this software for use within the Aerospace Industry. Under its new owner, MSC Software, it has grown to be a full-featured simulation package [4].

In his research, Diaz-Calderon [5] combines commercial simulation packages under three major categories: (1) block-diagrams, (2) object-oriented modeling and (3) bond graphs. He also points out that "Easy5 takes the modeling approach a step further in which the system is modeled by defining the interactions between components instead of between simulation blocks as with the block-diagram approach". In EASY5, models are built from basic mathematical blocks, such as summers, dividers, and integrators, and special systems-level components such as engines, transmissions, differentials, gears, pipes, orifices, actuators, heat exchangers, clutches, etc. All of these blocks are contained in the standard libraries [6]. Some of the libraries are listed in Table 1.

Table I Some Standard Libraries in Easy5

Libraries	
General Purpose	Interactive Simulation
Ricardo Engine	Ricardo Planetary Kit
Gas Dynamics	Aerospace Vehicle
Basic Hydraulic	Ricardo Power train Advanced
Thermal Hydraulic	Ricardo Electric Systems

Components are even grouped further within the aforementioned libraries. The groups for the general purpose library for a senior level undergraduate and graduate level engineering and technology program are listed in Table 2.

Table II Groups of Components in General Purpose Library

Groups	
Cont. Xfer Functions	Nonlinear Effects
Discrete Functions	Tabular Functions
Sum/Multiply/Divide	Logic
Integrators	Data Analysis

Controllers	Special Purpose
Switches	Math Functions
Function Generators	Struct./Forces

For example, the Sum/Multiply/Divide group contains Divider, Gain Block, Product, Multiply and Add (Multiplexed), and Summing Junction. Besides having standard libraries, Easy5 allows the modeler to create and build up user-defined libraries. Moreover, FORTRAN and C programming language code can be embedded to models. Components and program codes are designed to have inputs and outputs, which are used to connect them to each other as it is depicted in Figure 1.

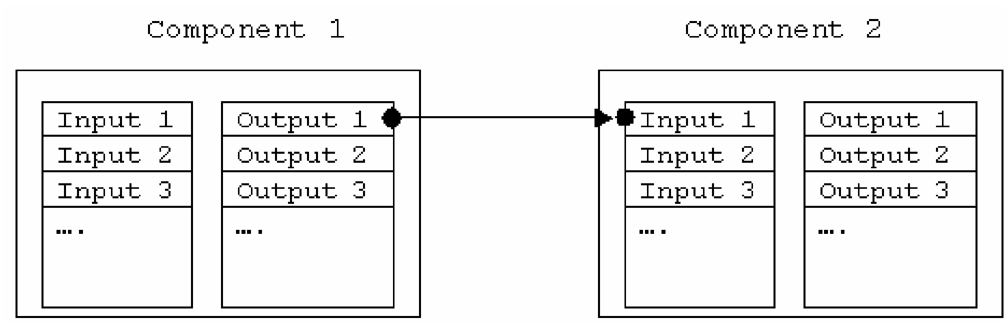

Figure 1. A schematic for connecting components in Easy5

After the network is completed by connecting components together, Easy5 creates an executable for the model. In most of the standard programming languages, an executable of the program can be operated independent of the programming environment. Whereas, the executable of an Easy5 model can only be run together with the simulation package, however, the same executable can be run for variety of different inputs.

III. Methodology and Design

A tractor model from a Midwest off-road machinery manufacturing company has been selected as a basis of this study, because of the availability of abundance of test data. Model development has been planned in such a way that it can be applied to other tractor models and other agricultural vehicles that consist of similar components.

Easy5 computer simulation package has been employed in developing the energy model of a tractor. Existence of a variety of components in available standard libraries, feature of creating models for non-standard components, and characteristic of its compatibility and connectivity with existent simulation packages (such as WAVE for engine simulation), gives us confidence that Easy5 is a powerful development tool in creating comprehensive energy models for off-highway machinery. The hierarchical structure for the tractor is shown in Figure 2. Each box represents either a component or a group of components.

Selected Tests

Available tests are determined for the tractor as PTO test, axle test, and wind tunnel high-speed transport test.

PTO test: Power-Take-Off (PTO) is a shaft mechanism in the back of a tractor, which is used for driving implements. In this test, the tires are removed from the tractor, PTO clutch is engaged and then a torque is applied to PTO shaft with an instrument called Dyno. The engine is kept running at 2200 rpm for 2 hours to make sure all components have reached a steady-state, this is called warm-up session. Finally six sets of measurements are taken for selected parameters with one-minute intervals. Some of the measured parameters are: Engine rpm, Fan rpm, PTO rpm and torque, Top tank temperature, Intake manifold temperature, Oil cooler inlet and fuel cooler inlet temperature.

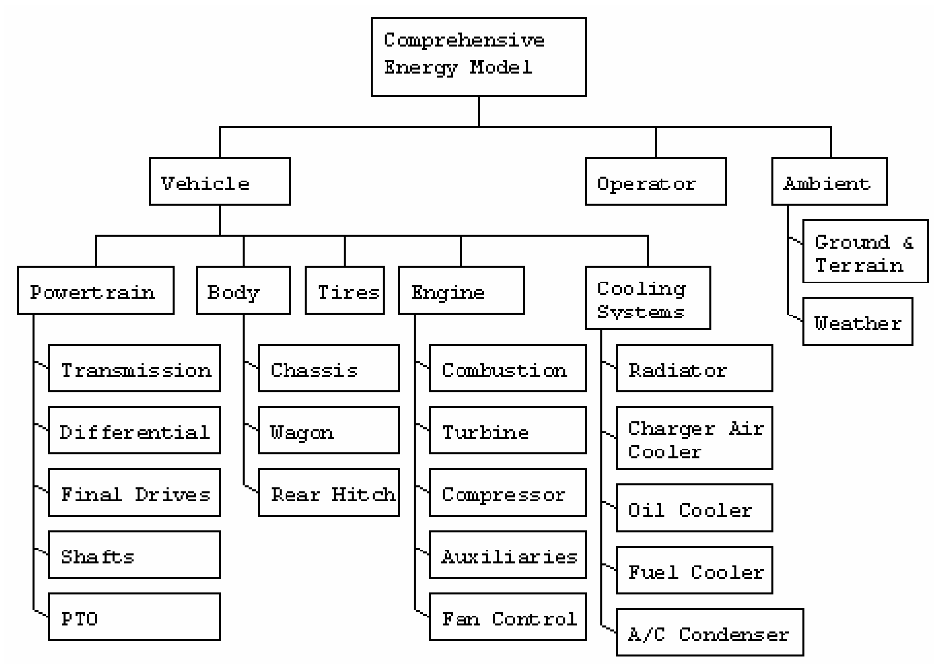

Figure 2. Hierarchical structure of vehicle model

Axle test: Axle test is similar to the PTO test with the only difference is that Dyno torque is applied to the rear axle final drive shafts instead of the PTO shaft. In order to apply torque to rear axles, the rear tires are disassembled from the tractor. The PTO clutch is disengaged to make sure no additional torque was applied. Transmission can be set at any desired gear. However for the AXLE test in this study the transmission gear is set to 9^{th} gear. The A/C is turned on. The wind speed is set to 11 km/h. The engine speed is set to 2200 rpm.

Wind tunnel high-speed transport test: Similar to the AXLE test, the transmission is set at the 16^{th} Gear and Dyno torque is applied to the rear axle to maintain 2200 engine rpm. The wind speed is set at 21.9 km/h in the wind tunnel. Ambient temperature is set to 40 ^{o}C. To maintain constant inlet fuel temperature at 40 ^{o}C, the fuel is supplied to engine from an external fuel housing not from the fuel tank. The A/C is turned on.

Development Strategy

Table III shows the needed components for a model build up from top to bottom. Thus the test, which needs the minimum number of components to be added, is the PTO Test. Accordingly, the

wind tunnel high-speed transport test requires that the maximum number of components added, as it requires vehicle components in addition to all the components listed in the previous two categories. This strategy enables the modeler to validate the model at the end of each stage.

Table III. Selected Tests and Their Required Components

Stage	Tests and Missions	Needed Components
1	PTO Test	- Engine - Transmission with PTO only - PTO drive - Vistronic Fan Drive - Radiator and Charge Air Cooler Circuits - Transmission Oil and Fuel Cooler Circuits - Recirculation of Air Effect - Controlled Torque Applied to PTO shaft
2	Hot Point Axle Test	- Transmission completed - Rear/Front Axle - Final Drives - AC Loop - Controlled Torque Applied to Rear Axle Final drives
3	Wind Tunnel High-Speed Transport Test	- Vehicle

IV. An Alternative Model for Engine

A complete high fidelity simulation model for this engine has been developed by engineers in the Midwest off-road machinery manufacturing company. Inputs and outputs required for incorporating WAVE engine model and Easy5 Comprehensive Energy model are listed as follows:

Inputs:
The input parameters are (1) the throttle setting which lets the driver to decide how much power is needed for operations, (2) the torque to flywheel which is a torque needed to drive the drive train, (3) air temperature inlet to filter, and (4) the ambient temperature and pressure.

Outputs:
The outputs are engine RPM, engine torque, fuel mass flow, air/fuel ratio, inlet air mass flow, temperatures and pressures at inlet and outlet of charge air cooler, compressor and turbine, temperature and pressure at intake manifold, temperature and pressure at exhaust manifold, heat rejected through charge air cooler (CAC), and heat rejected to the radiator coolant. Among these desired parameters, only heat rejection from CAC output could not be satisfied, instead it had to be estimated as an input to WAVE. WAVE engine model for 6-cylinder 8.1-liter diesel engine is depicted in Figure 3.

More over incorporating the WAVE engine model with the Easy5 Comprehensive energy model ended up with very slow simulation speed. An innovative approach has been developed to avoid the inconvenience due to the slow simulation speed while accurately predicting the heat rejection from charge air cooler (CAC). First, a new charge air cooler circuit has been developed in Easy5 by taking the schematic in Figure 4 as a basis.

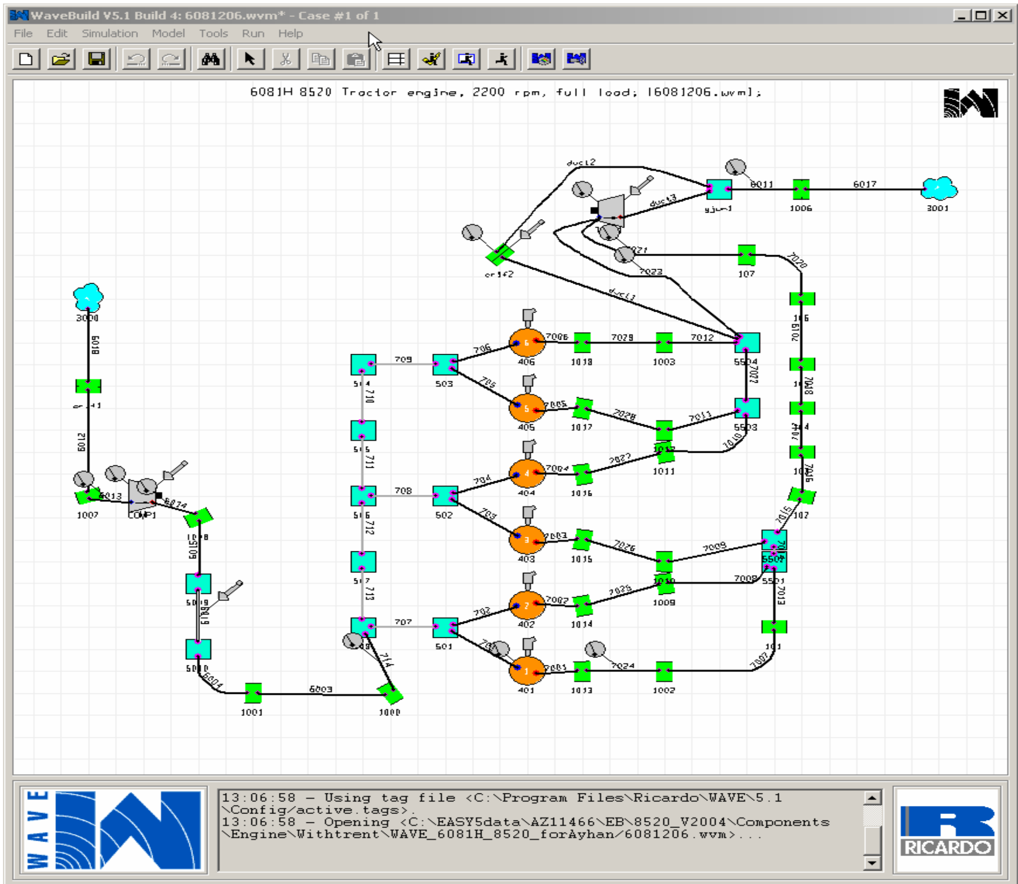

Figure 3. WAVE engine model for the diesel engine

The remarkable difference between the schematic in Figure 3 and the real engine is that the combustion module is replaced by a simple volume. In order to energize the turbine in this circuit, some heat (needed for CAC Circuit) should be applied to the volume.

Figure 5 demonstrates the input and output energies for a diesel engine on a simplified schematic of piston-cylinder mechanism. From conservation of energy by taking the volume cylinder and piston encloses as a control volume, we can write:

$$Q_{Fuel} = Q_{CAC\text{-}Circuit} + Q_{Gas\text{-}to\text{-}metal} + Q_{Brake} \qquad (1)$$

where, Q_{Fuel} is the rate of fuel energy, $Q_{CAC\text{-}Circuit}$ is the rate of energy dissipated from the CAC Circuit, $Q_{Gas\text{-}to\text{-}metal}$ is the rate of energy from gas-to-metal, and Q_{Brake} is the rate of the mechanical energy obtained from the engine.

The fuel energy is calculated as mass flow rate (kg/s) times the lower heating value of diesel fuel (J/kg). The lower heating value for the No. 2 diesel fuel used in the tests is 42,550,560 [J/kg]. The fuel mass flow rate is obtained by running the WAVE Engine model. The WAVE engine model also provides a good estimate for the heat for Gas-to-Metal that represents the heat rejected through the radiator.

Brake power is defined as the power obtained from the engine after all the losses and can be calculated as the torque delivered to drive train (Nm) times the angular velocity of the flywheel

(radian/s). Since all the other variables are known, equation 1 can be utilized in calculating the heat needed for CAC circuit. This heat directly is applied to volume replacing combustion and energizes the turbine. An Easy5 model of the alternative charge air cooler circuit is shown in Figure 6. A check valve is placed before the volume (the node component NO) to ensure no reverse flow from the volume to the heat exchanger.

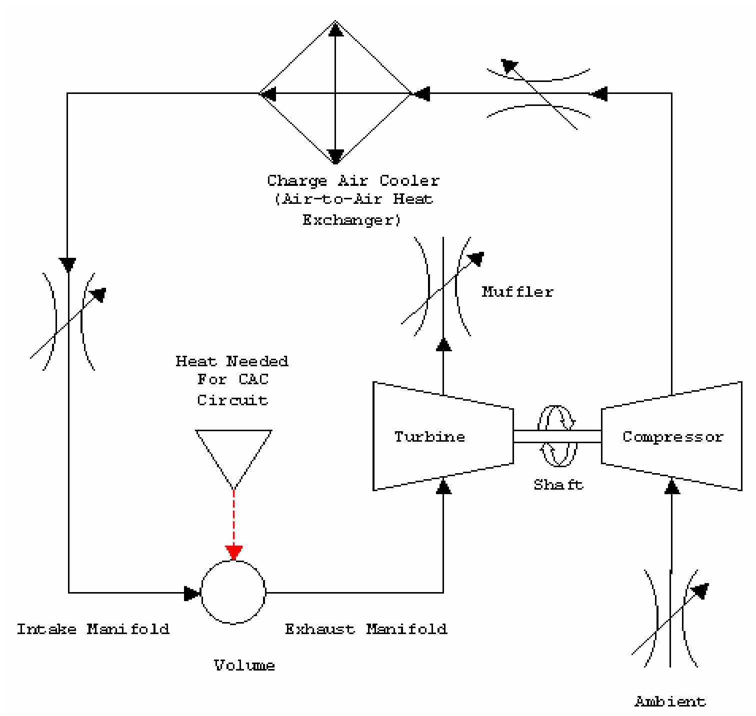

Figure 4. Alternative Charge Air Cooler (CAC) circuit schematic

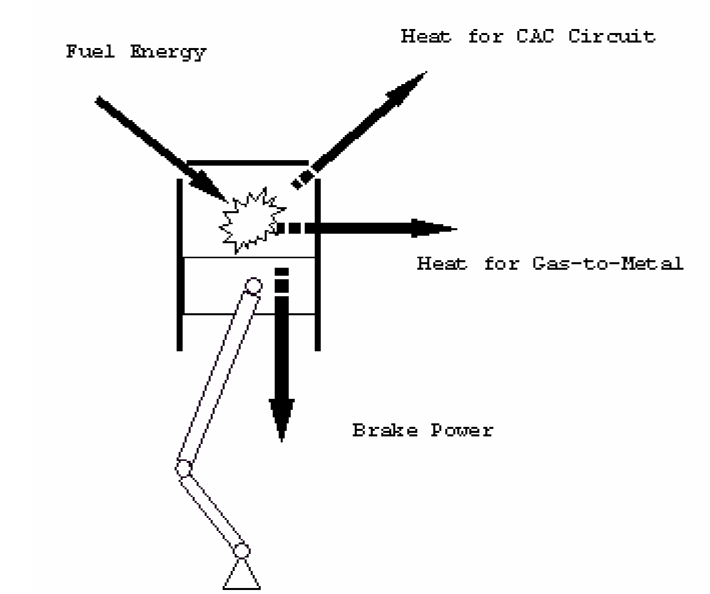

Figure 5. A schematic of energy balance for diesel engines

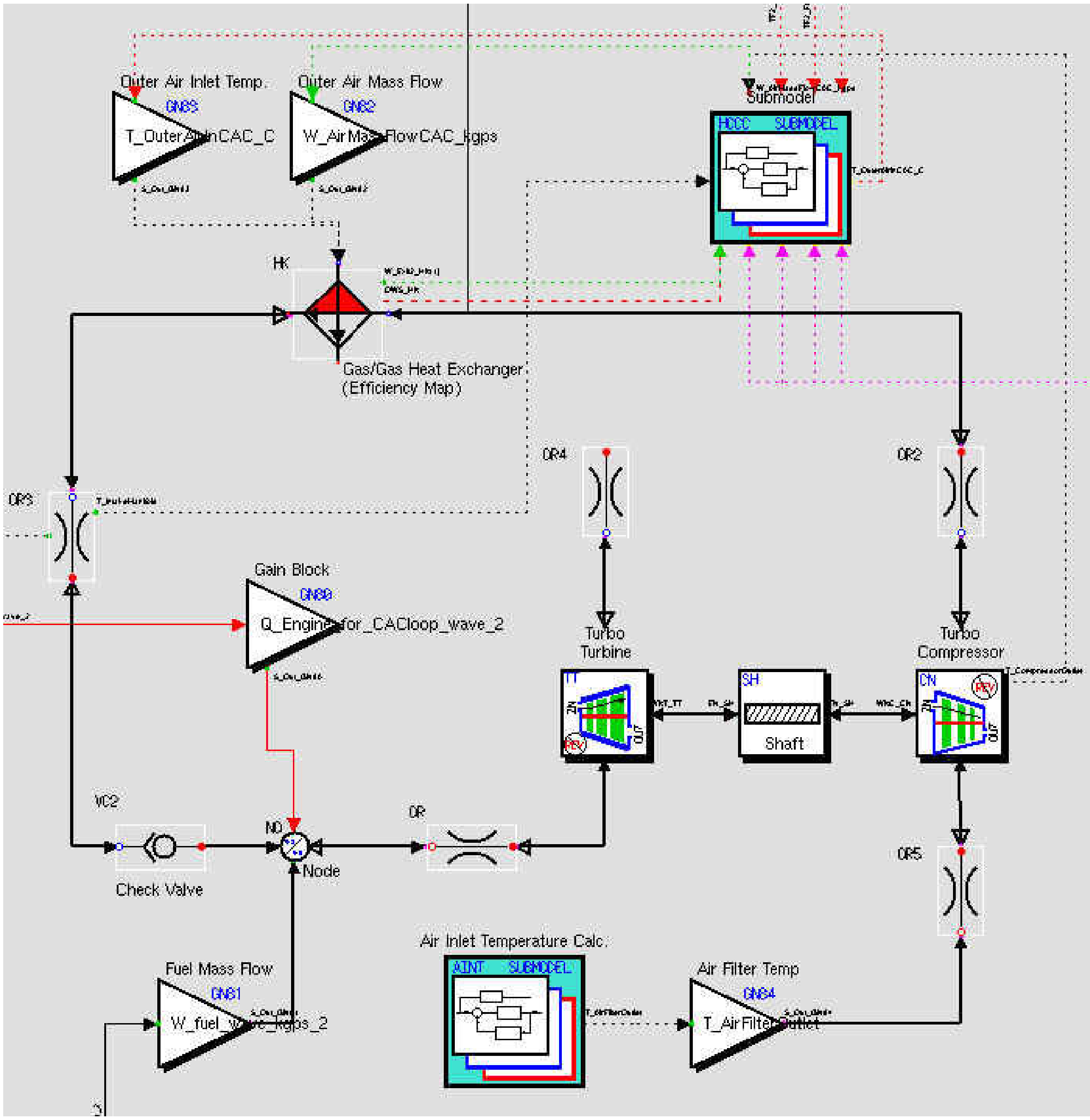

Figure 6. Easy5 model for the alternative CAC circuit

V. Comparing the simulation with test data

The PTO Test

In order to acquire results from the comprehensive energy model (CEM), three consecutive steps of simulation runs have been followed. First, the CEM was run for 5 minutes of real time to obtain a steady state torque applied to E3 -the simple engine - due to the load in PTO. The estimated heat rejection from the charge air cooler was also recorded. Secondly, these two parameters were used as inputs to WAVE engine model, which was run for 120 seconds of real time to obtain the estimated fuel consumption rate and the estimated heat rejection from the radiator. Finally, the CEM was run again by inputting the estimated fuel consumption rate and the estimated heat rejection from radiator. The results are listed in Table IV.

Table IV. Percentage Errors of the Simulation Results from the PTO Test Data

Parameters	Ave Test Data	Ave CEM	Percentage Error
Top Tank Temperature (ºC)	96.88	97.00	0.12%
Intake Manifold Temperature (ºC)	56.42	55.07	2.39%
Oil Cooler Inlet Temperature (ºC)	66.50	68.07	2.36%
Oil Cooler Outlet Temperature (ºC)	58.48	57.55	1.59%
Fuel Cooler Inlet Temperature (ºC)	48.93	49.20	0.54%
Fuel Cooler Outlet Temperature (ºC)	37.47	39.10	4.36%
Fan Speed (rpm)	1635.33	1651.83	1.01%
PTO torque (Nm)	1848.83	1843.95	0.26%

The AXLE Test

The simulation model was run in three steps as it was described in the PTO test. The results are listed in Table V.

Table V. Percentage Errors of the Simulation Results from the AXLE Test Data

Parameters	Ave Test Data	Ave CEM	Percentage Error
Top Tank Temperature (ºC)	108.8	108.3	0.46%
Intake Manifold Temperature (ºC)	69.8	69.9	0.21%
Oil Cooler Inlet Temperature (ºC)	88.2	86.1	2.34%
Oil Cooler Outlet Temperature (ºC)	77.3	75.8	1.90%
Fuel Cooler Inlet Temperature (ºC)	73.3	71.5	2.50%
Fuel Cooler Outlet Temperature (ºC)	61.9	58.5	5.52%
Fan Speed (rpm)	2399	2398	0.03%
AXLE Torque (kNm)	29.83	30.28	1.50%

The High Speed Wind Tunnel Transport Test

The simulation model was run in three steps as it was described in the PTO test. The results are listed in Table VI.

Table VI. Percentage Errors of the Simulation Results from the High Speed Wind Tunnel Transport Test Data

Parameters	Ave Test Data	Ave CEM	Percentage Error
Top Tank Temperature (ºC)	94.7	94.62	0.08%
Intake Manifold Temperature (ºC)	59.18	58.52	1.12%
Oil Cooler Inlet Temperature (ºC)	100.1	100.28	0.18%
Oil Cooler Outlet Temperature (ºC)	81.8	79.7	2.57%
Fuel Cooler Inlet Temperature (ºC)	44.25	44.55	0.68%
Fuel Cooler Outlet Temperature (ºC)	44.58	41.87	6.09%
Fan Speed (rpm)	2326	2324	0.07%
Engine speed (rpm)	2138.83	2138.70	0.01%

The proposed comprehensive energy model development is recommended and planned to be implemented in the process control laboratory at the University of Northern Iowa. It is expected that addition of this energy model development will positively impact student interests and enhance the students' ability to visualize simple actual process control simulators [7]. Many engineering and technology curricula include instrumentation, advanced CAD, and control courses using AutoCAD, LabView™ combined with a variety of instrumentation inputs from proximity sensors and other transducers provided a good learning tools for undergraduate and graduate students [8].

VI. Conclusion

Based on comparison of the actual test data and the comprehensive energy model outputs for selected critical parameters, the ±3% margin of error was found to be reasonable for the accuracy of the developed model. It was concluded that the comprehensive energy model is adequately representing the selected tractor model from the energy distribution and the component temperatures point of view. Only the fuel cooler outlet temperature was out of this margin, which leads the authors to conclude that a further refinement on the fuel cooling circuit was required. However, for the accuracy of the more important critical parameters, such as the top tank temperature and the fan speed, the margin of error was found to be less than ±1%.

The authors realize that the implementation of a similar educational energy simulator requires an initial capital cost. The authors believe that a quick and much economical approach for educational institutions would be modeling and implementation of the proposed model through an educational version of Easy5 software which may eliminate necessity of an actual and expensive energy simulator for an agricultural vehicle. Assuming more institutions are now using various software packages, this may bring an excellent enhancement to control systems, instrumentation and data acquisition curriculum. This study promises to be an excellent opportunity for senior and graduate students for EE, EET, and MET programs as well as other interdisciplinary approaches. Students with basic control system theory may gain a lot of useful pedagogical skills by applying energy strategies in a virtual environment.

References

[1] A Joint Venture of Industry and Government. Off-Highway Vehicle Technology Roadmap. U.S. Department of Energy. DOE/EE-0261, December 2001.
[2] Joshi, A., and Jayan, PG. Modeling and simulation of aircraft hydraulic system. AIAA Modeling and Simulation Conference and Exhibit, 05-08 August 2002, Monterey, California, USA.
[3] EASY5 Overview. Retrieved August 29, 2004, from http://www.adams.com/easy5/overview.html
[4] Favate, S. MSC Software/Boeing – 2: Buys Model, Simulation Software. Dow Jones News Service. Newswires, 201-938-5400.90, 2002.
[5] Diaz-Calderon, A. A Composable Simulation Environment to Support the Design of Mechatronics Systems. Unpublished doctoral dissertation, Carnegie Mellon University, Pittsburg, Pennsylvania, 2000.
[6] Society of Automotive Engineers. Dynamic system development tool. (Boeing Co.'s Easy5x software) (Simulation products/applications). Automotive Engineering, 58. November, 1992.
[7] Johnston R., "Equipping a Process Control Lab via Department Sponsored Senior Projects", Proceedings of the 2000 ASEE Annual Conference & Exposition, Session 3432.
[8] Aldana, C., Erevelles, W., "Implementation of a Laboratory Learning Module for Process Monitoring and

Control, Proceedings of 2001 ASEE Annual Conference & Exposition, Session 1426, retrieved from http://www.asee.org/conferences/search/00833.pdf.

Biographies

AYHAN ZORA

Ayhan Zora is a mechanical engineer employed at Technology Center, Deere & Company, Moline, Illinois. He completed his Doctor of Industrial Technology degree at the University of Northern Iowa in December 2004. Dr. Zora holds a BS in Mechanical Engineering from Istanbul Technical University, an MS in Industrial Engineering from Bosphorous University, and an MS in Mechanical Engineering from the University of Arizona, Tucson. Dr. Zora has been working on development of energy models for off-highway vehicles using ProE and Easy 5 at the University of Northern Iowa, and Deere & Company.

MOHAMMAD F. FAHMY

Dr. Mohammed F. Fahmy joined the university of Northern Iowa (UNI) in August 1983 as an Assistant Professor of Materials and Metallurgy. Currently he is a Professor and Department Head of the department of Industrial Technology. He has been serving as department head since 1998.
During his tenure at UNI, Dr. Fahmy served on numerous departmental, college, and university committees and task force commissions in different capacities as member or chair. His services covered a wide spectrum of activities at both the undergraduate and graduate levels in curricular, administrative, and outreach matters. His research interests are mainly in applied engineering materials, undergraduate students research, and academic interests in higher education. Such research efforts culminated in a joint US patent in reinforced composite plastics and publications in national and international peer-reviewed/refereed professional journals and proceedings. He received many honors and citations from regional, state, and national academic and professional organizations.

RECAYI PECEN
Recayi Pecen holds a B.S.E.E. and an M.S. in Controls and Computer Engineering from the Istanbul Technical University, an M.S.E.E. from the University of Colorado at Boulder, and a Ph.D. in Electrical Engineering from the University of Wyoming (UW). He has served as faculty at the UW, and South Dakota State University. He is currently an associate professor and program coordinator of Electrical and Information Engineering Technology program in the Department of Industrial Technology at the University of Northern Iowa. His research interests and publications are in the areas of AC/DC Power System Interactions, power quality, and grid-connected renewable energy applications. He is a member of ASEE, IEEE, Tau Beta Pi National Honor Society, and NAIT. Dr. Pecen was recognized as an Honored Teacher/Researcher in "Who's Who among America's Teachers" in 2004 and 2005. He was also nominated for 2004 UNI Book and Supply Outstanding Teaching Award, March 2004.

FARUK TABAN
Faruk TABAN is currently serving as an instructor at University of Nevada, Reno. He holds Ph.D. in Mechanical Engineering at University of Nevada, Reno, M.Sc. in Materials Engineering at University of Southern California and M.Sc. and B.Sc. both in Mechanical Engineering at Istanbul Technical University.