INTELLIGENT COMPUTER AIDED DESIGN, ANALYSIS AND IMPROVEMENT OF COOLING, HEATING AND POWER GENERATING SYSTEMS

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ABSTRACT

The design and analysis of cooling, heating and power generating systems are long and tedious. It is very necessary to obtain the cycle performance quickly and accurately. This paper describes the use of an intelligent computer aided software in design and analysis of these systems. Using the software increases engineers interest and design ability in these systems.

Usually when cooling, refrigeration, heating and power generating systems are designed and analyzed using the tradition way, much time is required for table or chart searching and calculations. As the computer become more available and sophisticated, various researchers have tried to solve this problem in order to save time. A software which is fast, flexible, intelligent and easy to use is necessary.

An ICAI (Intelligent Computer-Aided Instruction) software called CyclePad is developed to help with the conceptual design and analysis of thermodynamic cycles. CyclePad works in three (design, analysis and contradiction) modes. In the design mode, a graphical editor is used to place components taken from the inventory shop and connect them. When CyclePad is satisfied that the structure is fully laid out, the user can proceed to the analysis mode. In the analysis mode, the working fluid and modeling of each component are specified, and numerical values for the properties of components are then entered by the user. As soon as this information are provided, all performance characteristics of the system are displayed. A sensitivity analysis is also available in the CyclePad. An important aspect of carrying out an analysis is to check whether or not the results are physically meaningful. In such a case, CyclePad can use its intelligent knowledge to detect the conflict similar to a senior engineer catching junior engineer mistakes and enters the contradiction mode. CyclePad also has a coaching facility which allows the user to determine which of his assumptions contradicate to each other and why.

KEYWORDS, *Intelligent computer, cycle, design, analysis*

1.0 INTRODUCTION

Research in Cognitive Science potentially offers tremendous benefits in education. Artificial Intelligence (AI) research provides formal representations and reasoning techniques that can be used in new kinds of educational software which itself contains a deep understanding of the material being taught. These scientific advances, coupled with dramatic changes in computing technology provide new opportunities for exploring how intelligent software can be used in thermodynamics.

A new kind of educational software called articulate virtual laboratories (AVL) has been implemented into the engineering curriculum at the US Naval Academy since 1996. An articulate virtual laboratory is designed to help students learn thermodynamics by scaffolding them in conceptual design tasks, using a simulated environment to allow them to create and analyze designs for complex thermodynamic systems and using software coaches to provide guidance. It is believed that intelligent computer aided instruction (ICAI) teaching and design is not only in the future of education, but will be an effective improvement for engineering students.

2.0 ARTICULATE VIRTUAL LABORATORY

The rapid increase in the power of microcomputers combined with rapidly falling prices, provides the opportunity to apply recent advances in artificial intelligence technology to new kinds of educational software. By exploiting advances in qualitative physics, educational software can use methods and concepts similar to those used by domain experts, including the tacit knowledge of the domain. By exploiting advances in reasoning technology, particularly truth-maintenance systems, educational software can be built that explains the principles it uses. The ability of qualitative physics to provide computer-assisted modeling capabilities combined with efficient reasoning techniques means that educational software can work with new problems in the domain, without reprogramming. Such generality will empower students and instructors by enabling them to pose their own problems, and will thus provide a more motivating instructional context. By exploiting advances in analogical reasoning, we can use libraries of examples and previously-solved problems to provide a foundation for coaches that introduce students to appropriate problem-solving methods in a domain.

3.0 THE ROLE OF DESIGN

Design is the core activity of engineering. The ability to develop useful artifacts by understanding how to apply fundamental principles to applications is a major reason why engineering education is so important in today's highly competitive environment. Providing design experience is clearly essential for training engineers. However, design activities also provide powerful motivation for learning fundamental physical principles. Design requires using knowledge in an integrated fashion rather than memorizing isolated facts. Therefore, design provides a meaningful context for learning physical principles.

The most important class of educational software for engineering education is oriented around conceptual design activities. In engineering, conceptual design is the early phase which identifies the basic features of the design. This includes specifying the physical processes and principles by which the design achieves its goals, as well as performance estimates and rough cost estimates. Conceptual design occurs in every area of engineering. In thermodynamics, complex artifacts such as power plants, refrigerators, and heat pumps are treated as thermodynamic cycles.

Conceptual design is most appropriate for engineering education because it focuses on the fundamentals of a domain. On the other hand, detailed design is concerned with fleshing out the results of conceptual design, including figuring out the geometry of the system, detailed parts costs, operating and maintenance procedures for the resulting artifact, and all of the other issues which must be settled in order to build and operate the newly designed artifact. Engineering students need detailed design experience, of course. However, we believe that the largest pedagogical payoff will be in computer technology that simplifies broad-scale incorporation of conceptual design in engineering curricula. Conceptual design forces the designer to think directly about many of the major themes.

Despite the centrality of design in engineering, today's engineering curricula generally offer few design experiences. Some of the reasons come from the cost of, and sometimes danger in, building physical artifacts. A laboratory where students design and build their own jet engines, for example, is simply not feasible. Additional reasons that design exposure is limited include (1) the time-consuming nature of detailed design which strains already-overloaded curricula, and (2) the complexity of design which requires additional supervision to minimize unenlightening aspects of student explorations.

Virtual laboratories provide a partial solution to these dilemmas. A virtual laboratory is a software environment consisting of "parts" corresponding to physical parts, tools for assembling collections of these parts into systems, and facilities for analyzing and testing the systems. These software environments allow students to "build" their designs and try them out without expense or danger. Thus, these programs solve the cost and safety problems associated with design. However, they provide no coaching. They do not explain their results in qualitative terms that students can easily understand. They cannot teach students how to choose an appropriate model or how to build new models. They have no representation of the student's goals so they cannot assist the student in evaluating his or her design. Finally. they cannot help the student understand the connections between the simulation results and the fundamental principles used to generate those results. To overcome these 1imitations will require synthesizing artificial intelligence technology to develop articulate virtual laboratories, that is, intelligent learning environments with a deep understanding of engineering principles.

4.0 CYCLEPAD

CyclePad is the conceptual CAD component of the engineering thermodynamics AVL developed by Professor K.D. Forbus [1] of Northwestern University and evaluated by the author [2]. CyclePad scaffolds the activities of students who are learning how to design and analyze thermodynamic cycles. An inventory shop of parts (e.g., compressors, turbines, pumps, heat exchangers, etc.) are combined into networks, potentially generating an unlimited set of designs of thermodynamic systems. CyclePad performances the operational characteristics and sensitivity analysis of the system.

CyclePad is a conceptual CAD tool for visualizing and analyzing thermodynamic systems. Students construct their design by "wiring up" components and assigning numerical values for their parameters. For example, suppose a student wanted to make a simple gas turbine power cycle more efficient. To gain efficiency, the student might try making the combustion temperature higher. He might perform a sensitivity analysis, varying this temperature to see how efficiency is affected and what other consequences result. Making the gas turbine cycle by adding more intercoolers and reheaters look more like a Carnot cycle can yield even higher gains. A further modification, regenerative heating, gains even greater efficiency.

Due to the substantial amount of numerical calculation involved, students typically avoid exploring more than one or two alternatives and avoid performing advantageous trade-off studies. Since trade-off studies are one of the most effective means to building intuitions about thermodynamic systems, CyclePad’s value lies in the ability of the students to incrementally derive the consequences of assumptions and automating the work, thus relieving the student of the tedium of numerical calculations. Another major stumbling block for students is learning how to model, that is, how to make the simplifying assumptions needed to derive reasonable answers. CyclePad helps by making the choices for modeling assumptions explicit in its representation and depiction of the design. Therefore, the students are encouraged to consider what reasonable assumptions might be applicable. One benefit of Articulate Virtual Laboratories is to decrease students' primary difficulties and intuitive but faulty conceptions within the domain, based on empirical evaluations of their performance using AVLs.

CyclePad' s knowledge base captures a substantial fraction of the knowledge in introductory thermodynamics text. The knowledge base consists of representations for the components of thermodynamic systems and qualitative representations of the physical processes inside them.

5.0 USING CYCLEPAD FOR DESIGN AND ANALYSIS OF COOLING, HEATING AND POWER GENERATING SYSTEMS

Analyzing cooling, heating and power generating system is more meaningful, time saving and fun for students using quick-change simulation software such as CyclePad than the traditional, lengthy, complex and tedious method. in design. Students are able to change any parameter in the system and see the effect of the parameter on the performance of the system instantaneously. Design is an iterative learning process. By trial and error, students are able to choose various components in the design of power plants or choose different working fluids in the plants using CyclePad as a tool. They gained a tremendous amount of experience, confidence, and knowledge in a relative short time. Due to the quick iterative design abilities of CyclePad, instructors were able to assign more cycle analysis and design problems to their students.

6.0 EXAMPLES

6.1 Cooling system

An arrangement of either a cascaded or multi-staged refrigerator can be made as illustrated in Figure 1. In this arrangement, the system can be either a cascaded refrigerator or a multi-staged refrigerator.

Suppose $mdot_3$=0 and $mdot_8$=0, the working fluids of the top and that of the bottom cycle do not mix. The system is a cascaded refrigerator. Otherwise, it is a multi-staged refrigerator. Example 1 illustrates the system as a multi-staged refrigerator if $mdot_3$=1.

Example 1. A cycle as shown in Figure 1 has the following information:

working fluid=R134a, p_1=85 kPa, x_1=0, p_2=200 kPa, p_5=500 kPa, m_4=1 kg/s, m_{11}=0 kg/s, x_6=0, x_8=0 and x_{13}=1.

Determine the power required by compressor #1, power required by compressor #2, total power required by the compressors, rate of heat added in the evaporator, cooling load, and COP of the cycle.

Solution:

To solve the problem by CyclePad, we do the following steps:

(1) Build the cycle as shown in Figure 1.

(2) Assume compressors are adiabatic with 100% efficiency, heater and cooler be isobaric, and both hot-side and cold-side of the heat exchanger are isobaric.

(3) Input working fluid is R134a at state 1, p_1=85 kPa, x_1=0, p_2=200 kPa, p_5=500 kPa, m_4=1 kg/s, m_{11}=0 kg/s, x_6=0, x_8=0 and x_{13}=1.

(4) Display the cycle property results (Figure 2): The results are: COP=4.81, power input by compressor 1=-33.37 kW, rate of heat removed by the condenser=-193.9 kW, rate of heat added to the evaporator=160.5 kW, and cooling load=45.64 ton.

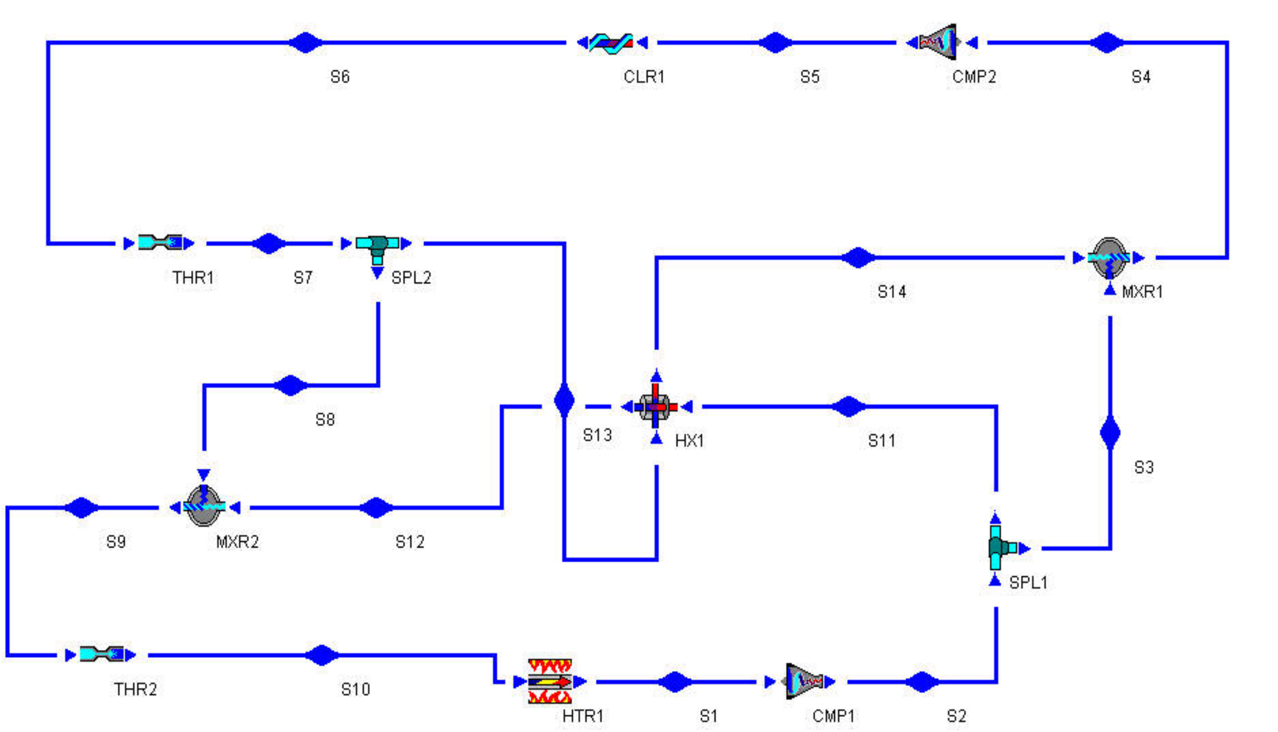

Figure 1. Cascaded or multi-staged refrigerator

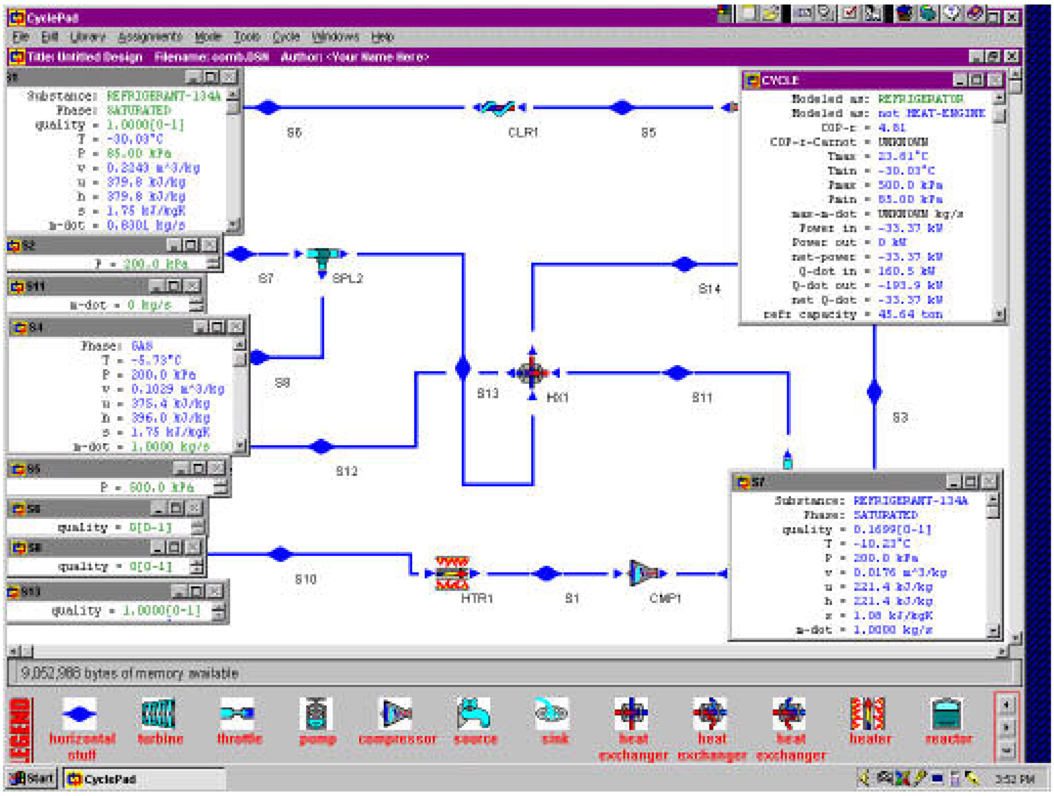

Figure 2. Cascaded or multi-staged refrigerator

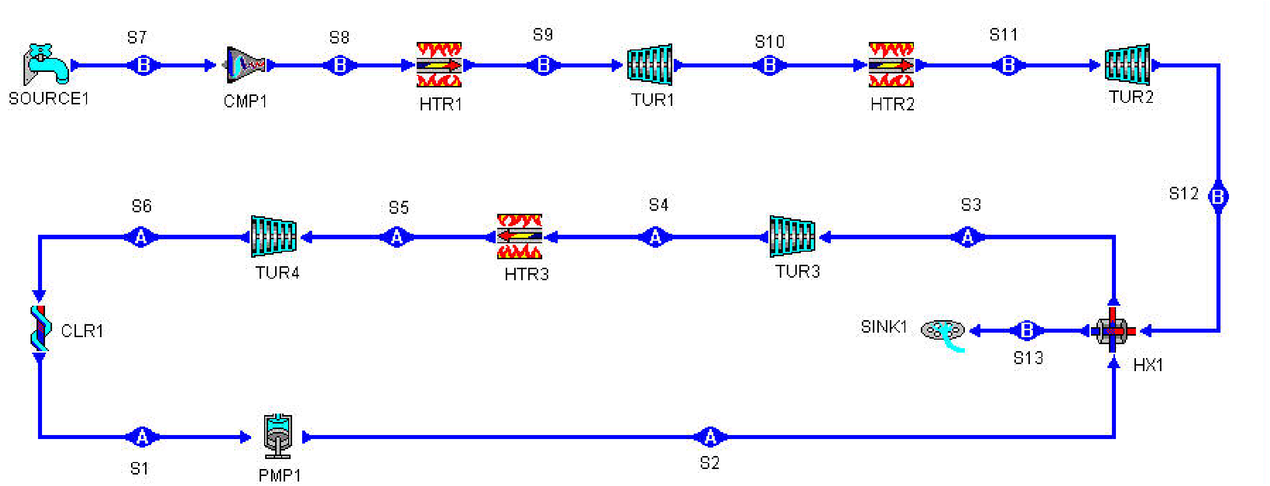

Figure 3. Brayton/Rankine cycle

6.2 Brayton/Rankine power generating system

Improvement on cycle efficiency can be achieved by using the hot exhaust waste heat of a high-temperature cycle to either partially or totally power a low-temperature cycle. One arrangement [3] of the Brayton/Rankine cycle which is a combination of a two-stage reheat Brayton cycle and a two-stage reheat Rankine cycle is shown in Figure 3.

Example 2. A Brayton/Rankine cycle (Figure 3) uses water as the working fluid with 1 kg/s of mass rate of flow through the Rankine cycle, and air as the working fluid in the Brayton cycle. In the Rankine cycle, the condenser pressure is 15 kPa (p_1); the boiler pressure is 8000 kPa (p_2); the reheater pressure is 5000 kPa (p_4); the superheater and reheater temperature (T_3 and T_5) are both 400°C. In the Brayton cycle, air enters from the atmospheric source to an isentropic compressor at 20°C and 100 kPa (T_7 and p_7), and leaves at 1000 kPa (p_8); air enters an isobaric heater (combustion chamber) and leaves at 1800°C (T_9); air enters a high pressure isentropic turbine and leaves at 600 kPa (p_{11}). Air enters a low pressure isentropic turbine and leaves at

100 kPa (p_{12}); air enters an isobaric regenerator and leaves at 500°C (T_{13}); and air is discharged to the atmospheric sink.

Determine the mass rate flow of air through the Brayton cycle, thermodynamic efficiency and the net power output of the Brayton/Rankine combined plant. Plot the sensitivity diagram of η (cycle efficiency) vs p_{11} (pressure at state 11).

Solution:

To solve this problem by CyclePad, we do the following steps:

(A) Build the cycle as shown in Figure 3. Assume the compressor, turbines and pump are adiabatic and isentropic, and the heater, cooler and regenerator are isobaric.

(B) Input working fluid=air, p_1=15 kPa, x_1=0, mdot=1 kg/s, p_3=8000 kPa, T_3=400°C, p_5=5000 kPa, T_5=400°C, p_7=100 kPa, T_7=20°C, p_9=1000 kPa, T_9=1800°C, p_{11}=600 kPa, T_{11}=1600°C, p_{12}=100 kPa, and T_{13}=500°C.

(C) Display results (Figure 4). The answers are: (1) Cycle A: η=37.52%, power input=-8.12 kW, power output=1165 kW, net power output=1157 kW, Qdot in=3084 kW; (2) Cycle B: η=47.79%, power input=-2267 kW, power output=8575 kW, net power output=6308 kW, Qdot in=13200 kW, mdot=8.28 kg/s; and (3) combined Cycle: η=55.79%, power input=-2275 kW, power output=9740 kW, net power output=7465 kW, Qdot in=13380 kW.

(D) Display sensitivity diagram (Figure 5) of η (cycle efficiency) vs p_{11}(pressure at state 11).

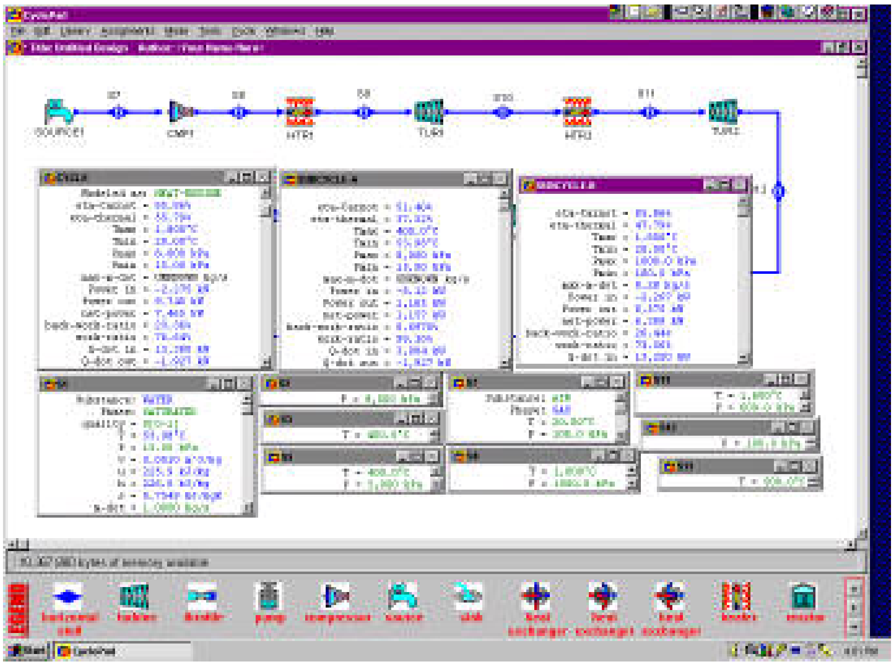

Figure 4. Brayton/Rankine cycle numerical example

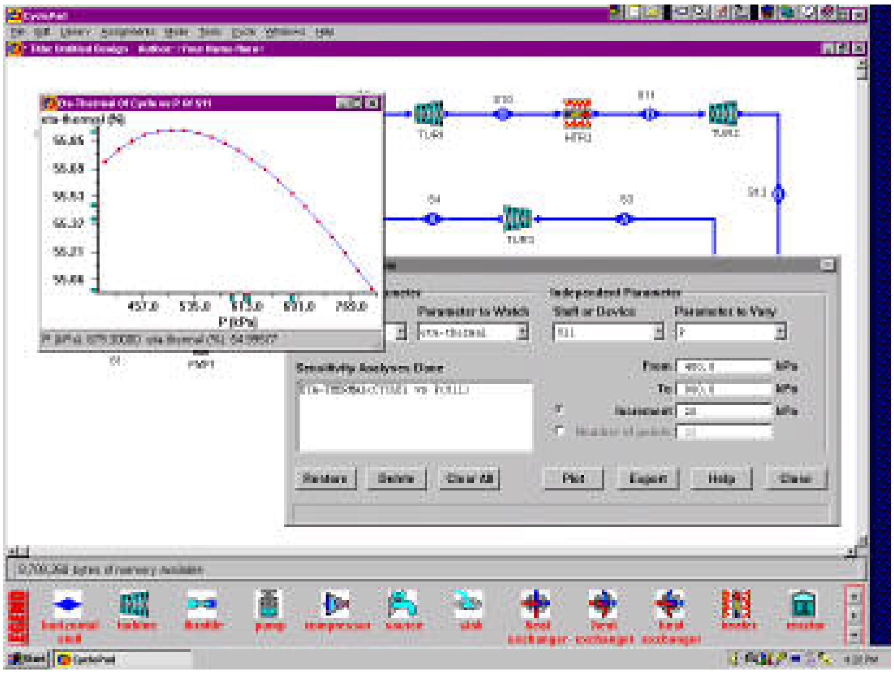

Figure 5. **Brayton/Rankine cycle sensitivity diagram**

6.3 Braysson power generating system

A Braysson cycle proposed by Frost, Anderson and Agnew [4] is an alternative to the Brayton/Rankine combined gas and steam turbine power plant. The Braysson cycle is a combination of a single Brayton cycle and an Ericsson cycle. The cycle takes advantage of the high-temperature heat addition process of the Brayton cycle and the low-temperature heat rejection process of the Ericsson cycle. It employs one working fluid in the two cycles in such a way that the full waste heat from the top Brayton cycle serves as the heat source for the bottom Ericsson cycle.

A design of such a novel Braysson cycle [5] consisted of four compressors, one combustion chamber, two turbines, and two coolers is shown in Figure 6.

Example 3. A Brayson cycle (Figure 6) uses air as the working fluid with 1 kg/s of mass rate of flow through the cycle. In the Brayton cycle, air enters from the atmospheric source to an isentropic compressor at 20°C and 1 bar (state 1) and leaves at 8 bar (state 2); air enters an isobaric heater (combustion chamber) and leaves at 1100°C (state 3); air enters a high pressure isentropic turbine and leaves at 1 bar (state 4). In the Ericsson cycle, air enters a low pressure isentropic turbine and leaves at 0.04 bar(state 5); air enters a first-stage isentropic compressor and leaves at 0.2 bar (state 6); air enters an isobaric inter-cooler and leaves at 20°C (state 7); air enters a second-stage isentropic compressor and leaves at 1 bar (state 8); and air is discharged to the atmospheric sink.

Determine the thermodynamic efficiency and the net power output of the Brayson combined plant. Plot the sensitivity diagram of η (cycle efficiency) vs p_6 (pressure at state 6) and sensitivity diagram of η (cycle efficiency) vs p_8 (pressure at state 8).

Solution:

To solve this problem by CyclePad, we do the following steps:

(A) Build the cycle as shown in Figure 6. Assume the compressors are adiabatic and isentropic, the heater is isobaric, the turbines are adiabatic and isentropic, and the coolers are isobaric.

(B) Input working fluid=air, p_1=1bar, T_1=20°C, mdot=1 kg/s, p_2=8 bar, T_3=1100°C, p_4=1bar, p_5=0.04 bar, p_6=0.2 bar, compressor inlet temperature=100°C, turbine inlet pressure=1000 kPa, turbine inlet temperature=1000°C, T_7=20°C, p_8=0.6 bar, T_9=20°C, and p_{10}=1bar.

(C) Display results (Figure 7). The answers are η=59.67%, and power input=-570.4 kW, power output=1075 kW, net power output=504.2 kW, Qdot in=845.0 kW.

(D) Display sensitivity diagram (Figure 8) of η (cycle efficiency) vs p_6 (pressure at state 6) and sensitivity diagram of η (cycle efficiency) vs p_8 (pressure at state 8).

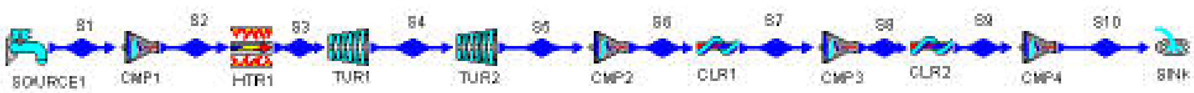

Figure 6. Braysson cycle

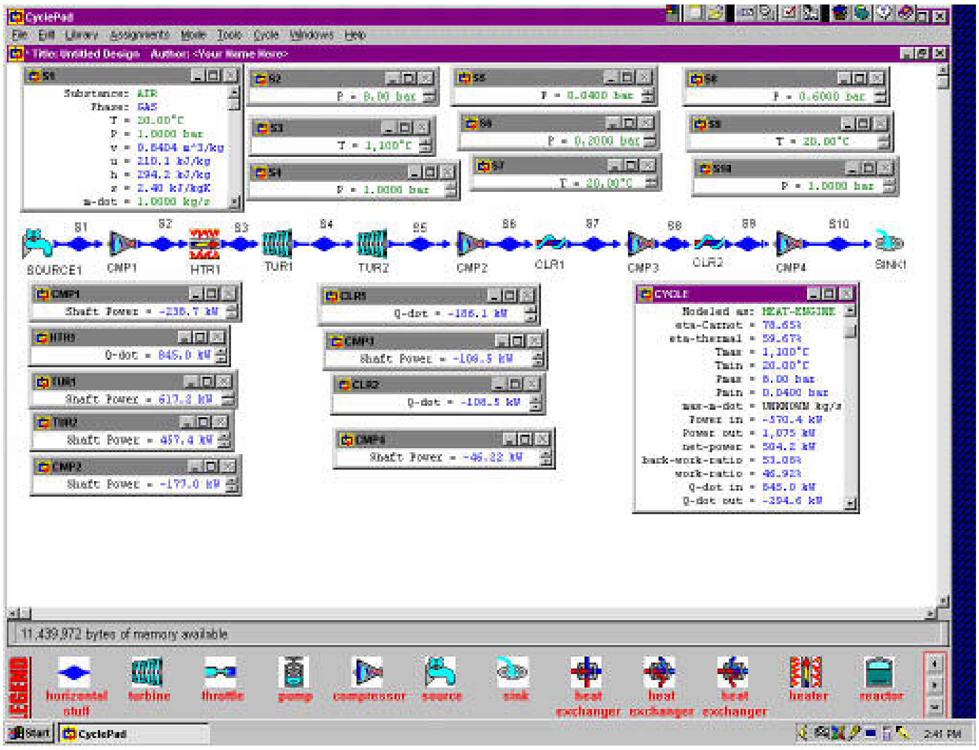

Figure 7. **Braysson cycle numerical results**

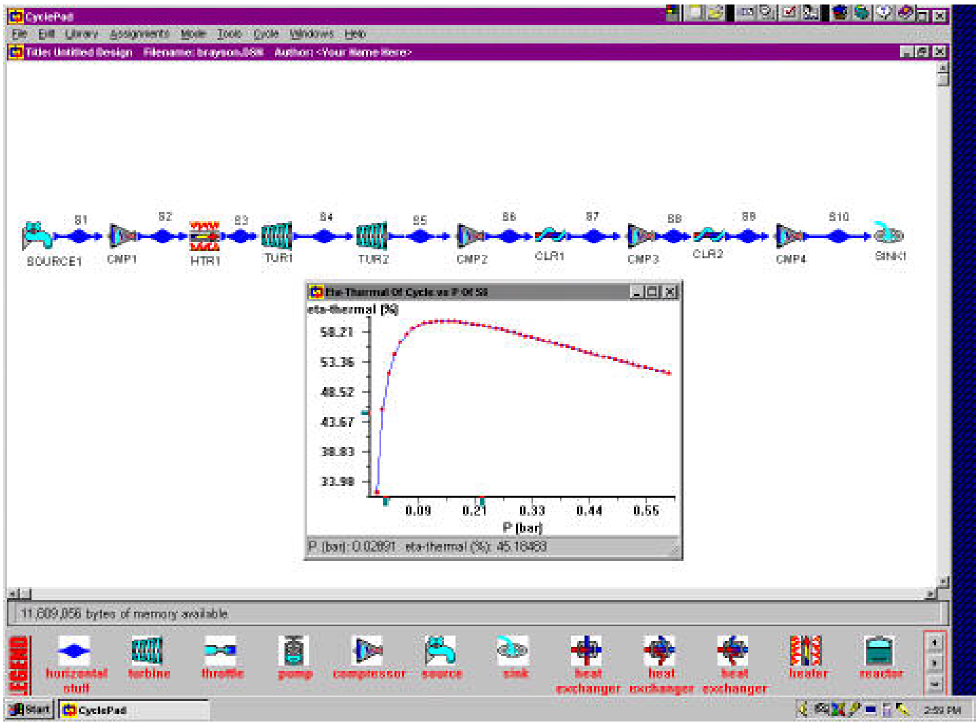

Figure 8. **Braysson cycle sensitivity diagram**

7.0 DISCUSSION

In the realm of thermodynamics, CyclePad is to a thermodynamist what a word processor is to a journalist. The benefits of using this software are numerous. The first is that significantly less time will be spent doing numerical analysis. As an engineer, this is much appreciated because computational work that would have taken hours before, can now be done in seconds. Second, as this paper has demonstrated, CyclePad is capable of analyzing thermodynamic systems with various working fluids. Third, due to its computer-assisted modeling capabilities, the software allows for individuals to immediately view the effects of varying input parameters, either through calculated results or in the form of graphs and diagrams, giving the user a greater appreciation of how a system actually works. More specifically, there is a feature that provides the user the opportunity to optimize a specified cycle parameter. This has been proven to be incredibly useful. Last, and most important, is the built-in coaching facility that provides definitions of terms and descriptions of calculations. CyclePad goes a step further by informing the user if a contradiction or an incompatibility exists between inputted parameters within a cycle and why.

When viewing the applicability of software of this nature on the drawing board, users could reap the benefits at all stages in an engineering career. For the young engineer just beginning the learning process, less time is spent doing iterations resulting in more time dedicated to reinforcing the fundamentals and gaining valuable experience. In the case of the seasoned engineer, who is well indoctrinated in the principles and has gained an "engineer's intuition", can augment his/her abilities by becoming more computer literate.

8.0 CONCLUSION

The intelligent computer software has been demonstrated to be a very effective tool in analyzing thermodynamic cycles. Any complicated cycle can be analyzed easily using CyclePad. The advantage of using CyclePad is not only does it provide quick and accurate cycle analysis predictions, but that it also forces the user to define each process in the cycle and to make reasonable input information to the cycle. Users using CyclePad in designing cycles could be freed from tedious table searching and hand calculations. They could spend more time doing optimization of operational parameters and selection of different combinations of working fluids of the thermodynamic systems.

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