PERFORMANCE MODELLING OF REFRIGERANTS
IN A VAPOR COMPRESSION REFRIGERATION CYCLE

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ABSTRACT

The simulation model based on the actual vapor compression cycle is performed in order to evaluate the performance of 14 refrigerants in terms of first law and second law efficiency. A 10% pressure drop is modelled in both the condenser and evaporator. The refrigerants that have been evaluated include R12, R22, R502, and their alternatives R134A, R401A, R401B, R402A, R402B, R404A, R407C, R410A, R408A, R409A, and R507. Effects of evaporating and condensing temperature on the COP, second law efficiency and irreversibility have been studied. The evaluation results show that R401A, R401B, and R409A are predicted as the best replacements for R12. R410A is predicted as the best alternative for R22, while R402B, R407C, and R408A are the best alternatives for R502 in terms of COP and second law efficiency. The results of actual cycle model show better predictions than that obtained with the ideal cycle model.

ABSTRAK

Model simulasi berdasarkan kitar pemampatan wap sebenar telah dihasilkan bagi tujuan menilai prestasi 14 bahan pendingin dari aspek kecekapan hukum pertama dan kedua. Kedua-dua pemeluwap dan penyejat telah dimodelkan dengan mempunyai kejatuhan tekanan sebanyak 10%. Bahan pendingin yang telah diuji termasuklah R12, R22, R502, dan bahan pendingin alternatif iaitu R134A, R401A, R401B, R402A, R402B, R404A, R407C, R410A, R408A, R409A, dan R507. Kajian kesan suhu penyejatan ke atas pekali prestasi, kecekapan hukum kedua dan ketidakbolehbalikan juga telah dijalankan. Hasil penilaian menunjukkan R401A, R401B, dan R409A sebagai alternatif terbaik mengantikan R12. R410A didapati alternatif terbaik bagi R22, manakala R402B, R407C, dan R408A untuk R502 dari aspek pekali prestasi dan kecekapan hukum kedua. Keputusan yang diperolehi menunjukkan model kitar sebenar dapat menghasilkan penilaian yang lebih baik berbanding model kitar unggul.

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LIST OF SYMBOLS

COP	Coefficient Of Performance
COP_{carnot}	Coefficient Of Performance of a carnot cycle
COP_{ref}	Coefficient Of Performance of a refrigeration cycle
COP_{rev}	Coefficient Of Performance of a reversible cycle
h	Specific enthalpy, $h=u+Pv$, kJ/kg
i	Specific irreversibility, kJ/kg
I	Irreversibility, kJ
$\dot{m}$	Mass flow rate, kg/s
P	Pressure, kPa
Q	Total heat transfer, kJ
$\dot{Q}$	Heat transfer rate, kW
Q_{evap}	Useful refrigerating effect, kJ
s	Specific entropy, kJ/kgK
S	Total entropy, kJ/K
T	Temperature, °C or K
T_O	Ambient temperature, °C or K
T_R	Refrigerated space temperature, °C or K
T_{surr}	Surroundings temperature, °C or K
u	Specific internal energy, kJ/kg
v	Specific volume, m³/kg
W_{net}	Net work, kJ
$\dot{W}$	Power, kJ/kg
η_{II}	Second law efficiency

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CHAPTER I

INTRODUCTION

1.1 Introduction

Chlorofluorocarbon (CFC) issues like ozone layer depletion and global warming have brought many studies for alternative refrigerants with suitable properties to replace the CFC and hydrochlorofluorocarbon (HCFC) refrigerants. Now, more new refrigerants are appearing on the market. This is due to the effort that has been made to find suitable replacements for CFC and HCFC refrigerants. R22 for example, is widely used in refrigeration system and being the most popular replacement for R12 which has been totally phase out by January 1, 1996 (unless for the continued use from existing and for continued production for very limited essential uses) [1].

As the production of R22 is being totally phase out by January 1, 2030, the rush to find its alternative continues. The study of performance evaluation of the R22 and its possible replacement has become important especially by compressor manufacturers. Before an experimental test in an actual system is carried out, the test through simulation program becomes useful as a preliminary evaluation of a refrigerant performance.

Comparison and evaluation of the performance of a refrigerant and its possible replacement, is done through the theoretical testing or testing in actual application [2]. Theoretical testing and comparison are usually made using a simulation program. Tests enable the performance of refrigerant alternatives to be evaluated across a broad range of operating conditions.

Theoretical testing would depend on refrigerant properties while an actual test would depend more on detailed specification of the equipment. The way refrigerants behave and perform in theory or simulation differs from which it perform in an actual system. However, a theoretical test is very useful as a preliminary evaluation before an extreme experimental test which involved a high cost is carried out in a full size equipment.

1.2 Refrigerants and Its Alternatives.

CFC and HCFC have taken the leading stand in refrigerating system since 1930s until early eighties. They became very popular and were found as the refrigerants with good performance compared with other refrigerants. However, by the eighties, CFC was considered as detrineutral to the environment, causing significant damage to the ozone layer. This resulted in the phasing out of the use and manufacture of CFCs, and later of HCFCs. It generates many studies as the search for alternative refrigerants with suitable properties to replace the CFCs and HCFCs. Continues now, many new refrigerants have been produced and commercialized by refrigerant manufacturers like DuPont, ICI, and Honeywell. Most of them are hydrofluorocarbons (HFC) which do not contain chlorine and have zero Ozone Depletion Potential (ODP).

The most common CFCs and HCFC that are being phased out are R12, R22 and R502. R12 is used in domestic refrigerators and freezers, and in automotive air conditioners. The most popular alternative for R12 when the CFCs phase out began is R22. It is pure fluid and has a very good efficiency characteristic on medium temperature range applications. But when the phase out of R22 began, the search for R12 alternatives continues. There are several alternative refrigerants that are potential substitutes for R12 and most of them are mixtures but some are pure fluids. They include R134A, R401A, R401B, R402B, and R409A.

R22 which is a HCFC is widely used in window air conditioners, heat pumps, air conditioners of commercial building and in large industrial refrigeration systems. It is considered as transitional or "interim" alternatives and has a high performance characteristic. Its contain chlorine and will eventually be phased out but can be

manufactured and used until 2030. The "long-term" alternatives for R22 that have been produced are mostly mixtures that do not contain any chlorine such as HFCs. They include R404A, R407C, R410A, and R507. R407C was the first to replace R22, but it was found out in recent research that new replacements R410A and R404A show better performance compared to R407C.

Other pure fluids alternatives for R22 are ammonia (R717) and propane (R290). Ammonia has been used for over 100 years. It is a low cost refrigerant with excellent thermodynamic properties and zero ODP. But it is toxic and flammable. Similar to ammonia, propane is no longer of interest because it is flammable even though it has similar thermophysical properties as R22 [2]. Other HCFC that has been considered is R134A which is a widely used as substitute for R22 in large chillers, as well as in automotive air conditioners and refrigerators.

R502 which is a blend of R115 and R22 is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets because it allows low evaporating temperatures while operating in a single-stage compressor. One of the replacements that have been produced for R502 is R404A. As discussed by David Wylie and Davenport [2], the data of Alternative Refrigerants Evaluation Program (AREP) indicates that R404A has about the same capacity as R502 at lower condensing temperatures, but rapidly decreasing at higher condensing temperatures. For a fixed evaporating temperature, R404A has a lower efficiency when condensing temperature increase compared to R502. It has less efficiency when compared to R502 at high condensing temperature. Other mixtures that have replaced R502 include R402A, R402B, R407C, R408A and R507.

1.3   Performance Evaluation of Refrigerants in Refrigeration Cycle.

The study of refrigerant performance is very important because the behaviour of refrigerants or refrigerant mixtures strongly influence the design of the refrigeration system. Different refrigerants have performed differently based on their thermodynamic properties and behavior. According to Vaisman [3], different refrigerants shows different heat transfer ratios and pressure drops in condensors and evaporators.

Yana Motta and Domanski [4], reported on how the refrigerant's critical temperature affects the refrigerant performance in the vapor compression cycle. As shown conceptually in **Figure 1.1**, differences in refrigerant's critical temperature and the shape of the two-phase dome on T-s diagram explain the different performance trends of the refrigerants.
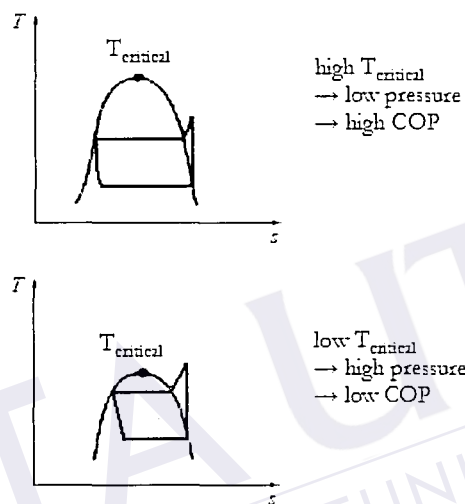
Figure 1.1 : Impact of critical temperature of volumetric capacity and COP [4].

For the same condensing and evaporating temperature, a fluid with a lower critical temperature will tend to have a higher volumetric capacity and a lower Coefficient of Performance (COP) while a fluid with a higher critical temperature will tend to have a lower volumetric capacity and a higher COP. The difference in COPs is related to the different levels of irreversibility on the superheated-horn side and at the throttling process. These levels of irreversibility vary with operating temperatures because the slopes of the saturated liquid and vapor lines change, particularly when approaching the critical point [4]. These are important issues besides considerations like safety, availability, and cost.

The performance comparison which was carried out by simulation had been done by many researchers in terms of first law and second law analysis. Yana Motta and Domanski [4] studied the performance of refrigerant R22 and its possible replacements which are R134a, R290, R410A and R407C in an air-cooled air conditioner system. All

these refrigerants have been evaluated using the NIST's simulation program Cycle 11. The study focuses on the COP and the effect of outdoor temperature on system capacity. It includes performance results for the basic cycle and for the cycle with a liquid line and suction line heat exchanger. The result shows a decreasing in system performance with increasing outdoor temperature. It also shows that the fluids with a low critical temperature experience a larger degradation of cooling capacity.

Vaisman [3] has presented the performance evaluation of R22 and R407C in an air conditioner system with a rotary vane compressor. The exergy approach is applied and performance evaluation is produced taking into account the actual system configuration including compressor data, coil's design, suction line, discharge line and liquid line design, and the data from the fan and blower. The result shows that R407C is compatible with R22 in terms of air conditioner performance.

Spatz and Yana Motta [5] evaluated the performance of R22 but in medium temperature refrigeration systems with its potential alternatives of R410A, R404A, and R290. The studies include thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, system performance comparisons using a validated detailed system model, safety issues, and determination of the environmental impact of refrigerant selection. The result shows that the R410A is an efficient and environmentally acceptable option to replace R22 in medium temperature applications.

Stegou-Sagia and Paignigiannis [6] have focused on exergy analysis of 10 working fluids including R401B, R401C, R402A, R404A, R406A, R408A, R409A, R410A, R401B, R410B and R507. The performances of these mixtures have been compared with the old refrigerants they replace which are R12, R22 and R502. When comparing the exergy efficiencies at constant evaporating temperature, the exergy losses of old refrigerants are found lower. The compression process has been predicted as the process which involved higher exergy losses followed by condensation process. R406A shows the highest value of exergy efficiency, while the lowest value is belongs to the mixture R409A.

C.K Sia [7] has developed a simulation program based on an ideal cycle to evaluate the performance of R12 and its possible replacements R134A and R401A, R22

and R407C, also R502 and its replacements R402A and R402B. The performance evaluation is focused on COP, second law efficiency, irreversibility, and discharge temperature. The predictions show that R134A as a good replacement for R12, R407C for R22, and R402A for R502.

1.4   Simulation Model of Refrigerants Performance Evaluation.

As described by Domanski and McLinden [8], there are a number of methods that might be used to predict the refrigerant performance. The simulation cycle can be modeled as a Carnot cycle, ideal, actual or actual cycle with detailed equipment specification. Carnot cycle is the simplest cycle analysis. It represents the refrigeration cycle which operates between two constant low and high temperatures. This cycle assume reversible compression and expansion processes, with isothermal heat supply and heat rejection.

An ideal cycle is modeled as a constant pressure and temperature process in the condenser and evaporator. Refrigerant leaves the condenser as saturated liquid and leaves the evaporator as saturated vapor. It does not consider the subcooling process at the condenser outlet and superheating process at the compressor inlet. The compression process is modeled as an isentropic process.

An actual cycle model normally considers at least subcooling and superheating processes. Refrigerant leaves the condenser as liquid and enters the compressor slightly superheated. Besides the isentropic compression process, the process in the compressor can be modeled as having isentropic efficiency. Other components such as liquid line and suction line heat exchanger may be included. Both the ideal and actual cycle usually needs a complete set of thermodynamic properties data [8].

For an actual cycle with detailed equipment specifications, it needs more detailed information on the actual system configuration. As presented by Vaisman [3], the actual components data such as compressor performance data, design parameters of evaporator and condenser coils, performance of fans and blowers, and, suction line, discharge line

and liquid line design must be taken into account. The thermodynamic cycle is defined with actual pressure drops in condenser, evaporator and suction line.

The Alternative Refrigerant Evaluation Program (AREP), an international cooperative program designed to identify alternative refrigerants for R22 and R502, which is coordinated by Air Conditioning and Refrigeration Institute (ARI), established the testing and performance evaluation methodologies. As discussed in [2], the four phases of AREP tests that can be used as a guidelines to improved the simulation model are ;

i. Firstly, determine how well a given compressor operates with a particular refrigerant by evaluates the performance of possible alternative in compressors using calorimeter testing.
ii. Second, the refrigerant is tested in existing refrigeration systems in "drop in" tests without any modification to the system equipment.
iii. Then, perform the heat transfer tests for the refrigerant under various operating conditions during both condensing and evaporating stages. These tests measure refrigerant-side heat transfer coefficient in "enhanced tubes".
iv. Finally, use the data from the three tests in system computer simulation and apply the information to improve the computer model in order to achieve a very fair prediction result of actual system.

The refrigerant performance evaluation and comparison can be used as a tool to evaluate the impact of components modification on the system performance. This model can provide very close information to the actual laboratory test. Beside the thermodynamic properties, a complete set of the transport properties data is also needed [8].

Many simulation programs have been developed to evaluate the performance of refrigerant and refrigerant mixtures in the vapor compression cycle. One of them is called Cycle 11. As reported by Domanski and McLinden [8], it is an evolution from the earlier model, Cycle 7, which is developed by McLinden at the National Institute of Standards and Technology (NIST), U.S.A. They called it a semi-theoretical model and the name refers to the eleven state point of the cycle model as shown in T-s diagram in **Figure 1.2**.
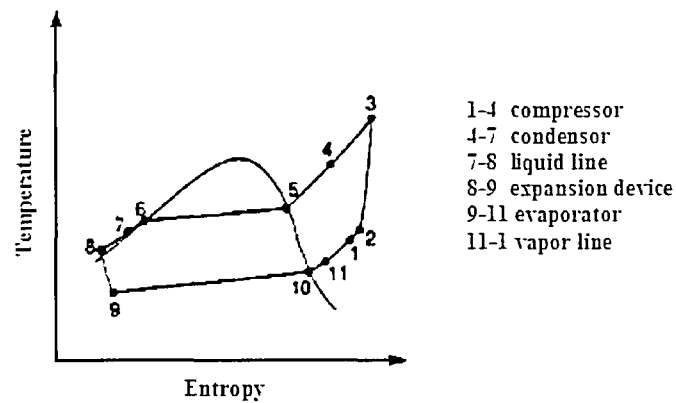
1-4 compressor
4-7 condensor
7-8 liquid line
8-9 expansion device
9-11 evaporator
11-1 vapor line

Figure 1.2 : Vapor compression cycle simulated by Cycle 11 [9].

The model performs simulation for user-specified temperature profile of the heat source and heat sink. The cycle consists of a basic cycle with an isentropic compression process, isobaric heat transfer in liquid line and suction line heat exchangers, and an irreversibility adiabatic expansion process. The user may specify a cross-flow, counter-flow, and parallel-flow evaporator and condenser with refrigerant subcooling and superheat, where appropriate.

The compressor model has three option type of compression process. They are isentropic, polytropic or either of these processes with the inclusion of volumetric efficiency and a representation of the heat transfer to the suction gas and from the discharge gas which occurs in a hermetic compressor.

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The output of the model includes thermodynamic properties at the key cycle points, capacities, and the COP of heating and refrigeration. This program employs FORTRAN subroutines from a NIST's REFPROP database to calculate refrigerant thermodynamic properties.

Other simulation programs that have been published is SERCLE (single evaporator refrigerator cycle model) [9] and Cycle D which is quite similar to the Cycle 11 program. **Figure 1.3** shows the interface of the Cycle D simulation program. Cycle D is a design tools used to simulate the vapor compression refrigeration cycle produced by NIST [10].
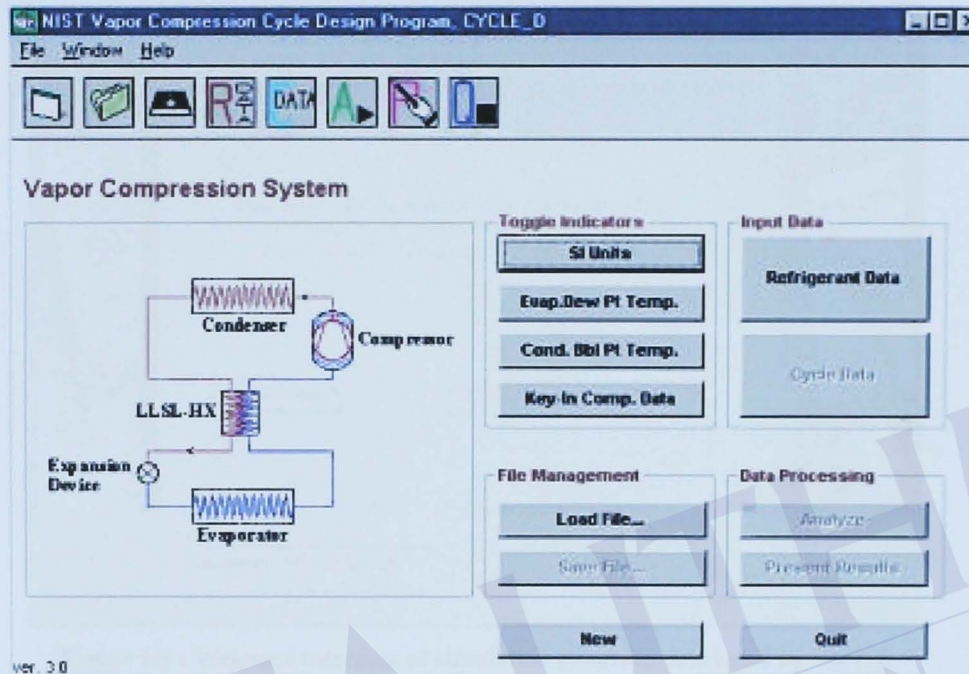
Figure 1.3 : Main graphic user interface (GUI) of Cycle D [10].

C.K Sia **[7]** has developed a simulation program called "Second Law Analysis of Refrigerant". The simulation model is based on the ideal cycle and focussed on exergy analysis of refrigerant in a vapour compression cycle. The main interface of the program is shown in **Figure 1.4** while **Figure 1.5** is input interface and **Figure 1.6** is one of the output interfaces.
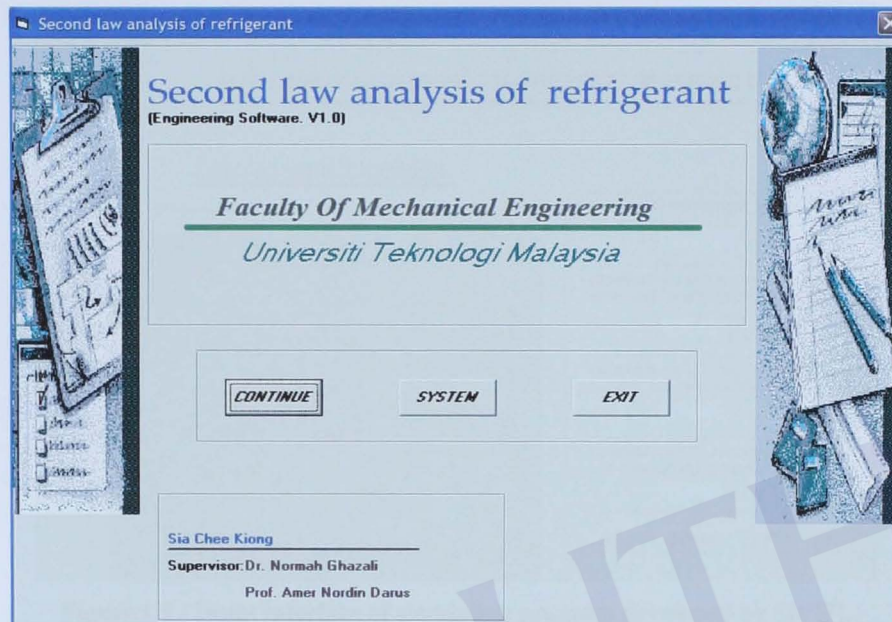
Figure 1.4 : Welcome interface of simulation program developed by Sia [7].

As shown in **Figure 1.5** and **1.6**, the inputs of the simulation program include condensing pressure, suction pressure, discharge temperature and ambient temperature. The outputs include energy balance in compressor, condenser, and evaporator, irreversibility and second law efficiency of each component. Other output includes thermodynamic properties at each state point which shows in other program interface.
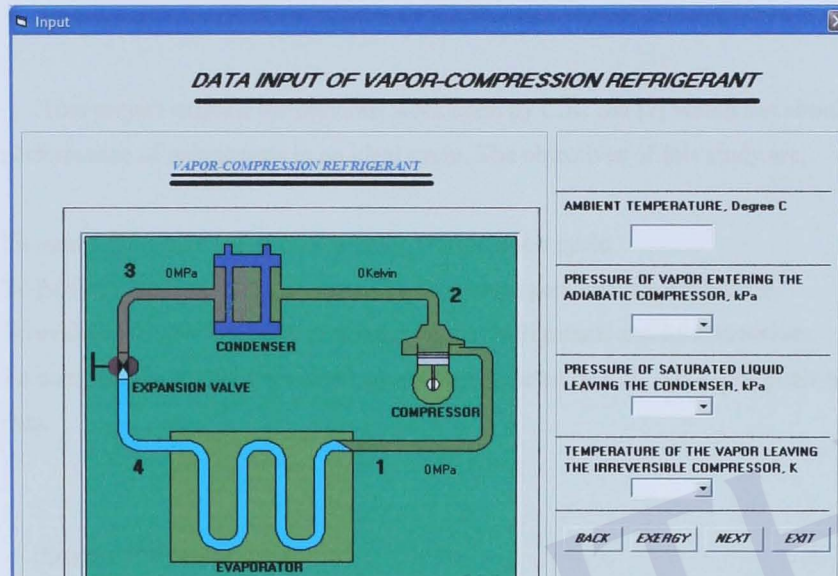
Figure 1.5 : Input interface of simulation program developed by Sia [7].
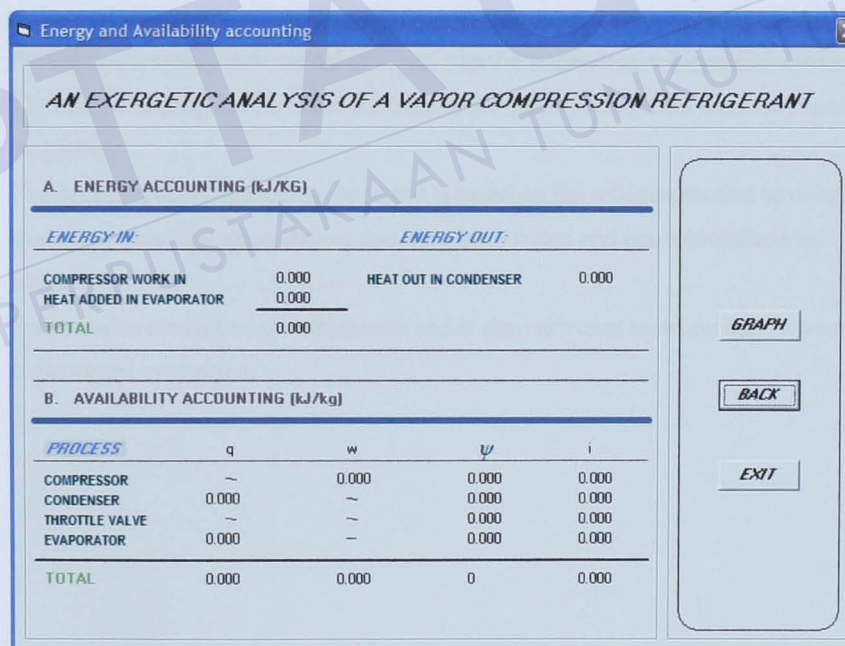

Figure 1.6 : One of the output interfaces of simulation program developed by Sia [7].

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