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A Code Development for PWR Efficiency Analysis and Energy Conversion Process Simulator

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Abstract

Nuclear Power Plant is the energy producer which converts the nucleus binding energy to heat energy and then converts to the electrical energy. The conversion process from heat energy to the mechanical energy and then becomes to the electrical energy, is an important process. The main problem is how much the heat energy can be converted to the work which is known as the efficiency of the energy conversion. The other problem is how the energy- conversion process on the turbine-steam generator system takes place. The efficiency analysis includes the saturated steam data reading, and repeating calculation, which are very tedious if they are done by manual calculation. In such a manner, the energy conversion process includes the efficiency conversion, nozzel process, and valve calculation, therefore a computer code for calculation process is needed. This research is directed to a computer code development for the heat to work conversion analysis and for heat conversion process simulation. This software is based on the Rankine cycle of saturated steam, the nozzel thermodynamics on open cycle, and the fluid flow in the valve. Among the input processes are the steam pressure on the turbine inlet, the vacuum pressure in the condenser, the amount of the regenerator, the electrical power, and the reheater temperature. The result is displayed as entropy versus temperature graphical, which shows the variation of pressure, temperature, and the steam flow rate along the Rankine cycle. The total steam flow rate for a certain power is also displayed on the monitor. This variable is also displayed in the block diagram of the simulator. The pressure, temperature, and the steam consumption determine the amount of the total thermal energy which should be generated in the reactor core, determine the turbine and pipe size, where these variables are used on the next design process step. Using this software, the energy conversion calculation on the nuclear power plant could be done easier and faster.

Keywords: *Rankine cycle, Regenerator, Reheater, Entropy, Efficiency*

1. Introduction

The main problem in the balance of plant on the nuclear power plant is energy conversion, from the heat energy to the electrical energy. The heat energy is potential energy which exists in the steam pressure, and the electrical energy is generated from the mechanical energy. The energy conversion of the potential energy in the form of the steam pressure to the mechanical energy in the turbine follows a complex process.

This energy conversion includes many processes. The primary processes are the Rankine cycle process, the nozzel process, and the valve process. The processes are non linear interdependence, so that the analytical description is difficult to be done. For easier understanding of the existing process, the computer code program simulator is needed.

This research describes the fundamental concept of the simulator which describes the energy conversion process of the turbine steam generator. The main process is a Rankine cycle with six regenerators and a reheater, where the steam expansion on the turbine is assumed as isotropic process. The highest feed water temperature is calculated by Salisbury formula, and the steam extraction is taken at the same temperature different.

The turbine process is assumed as the nozzel thermodynamic process, where the pressure degradation is assumed as linear process in all steps. With the nozzel theory, the relationship between the pressure, cross-section area, and the turbine power will be formulated. The valve function is to degrade the steam pressure from the steam generator to the turbine by the flow rate restriction.

This process is also means that the valve function is to regulate turbine power. The pressure, the temperature, and the flow rate at many important positions will be displayed at monitor, so that the value of the unit can be viewed easily.

2. Concepts Overview

The three concepts in this simulator software, that are Rankine cycle, nozzel, and the valve theorem, which become the basic of the software development are described in this paper.

2.1 The saturated steam Rankine cycle

The described Rankine cycle is the Rankine cycle for the saturated steam. This cycle is different with the fossil energy generation, where in this cycle, the superheated steam is used, whereas in the nuclear power plant, the dry saturated steam is used.

The block diagram of Rankine cycle at the turbine-steam generator system can be viewed in **Figure 1**. High pressure steam of 54 bar coming from a steam generator flows into the high pressure turbine, expands until about 10 bar pressure[1].

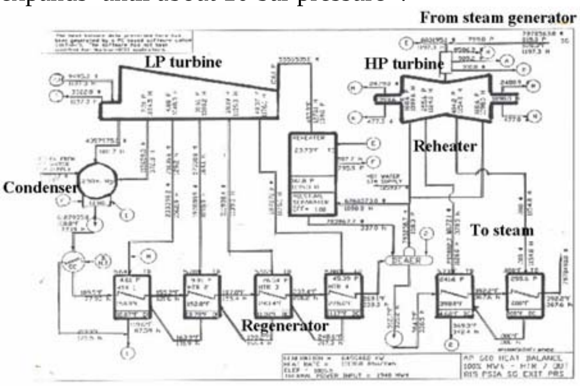


Figure 1. Block diagram of the Rankine cycle at NPP

The part amount of the steam is extracted and the rest goes through the process of low pressure turbine. The extracting steam heats the feed water that comes from the condenser to steam generator. Whereas the rest steam which goes through the low pressure turbine will undergo the water reducing and heating process.

After expanding at low pressure turbine, the steam flows into condenser for condensation process which changes the steam to water, and then is pumped to regenerator. Because the condensation temperature is close to environment temperature, about 40 ^oC, the condenser pressure is vacuum at 0.08 bar.

During the flowing process in the regenerator (there are six regenerators), the water absorbs the heat which comes from the extracted steam from low pressure turbine, where the former temperature of 40 ^oC rises to 232 ^oC. Beside that process, the trapped air in the water is separated and released in the generator. Whereas in Figure 2, the thermodynamic of the saturated steam Rankine cycle is shown at entropy versus temperature diagram.

The leaving water from condenser at point 1 will be pumped to steam generator at point 2.

From point 3 the water is heated in the steam generator where the former temperature of 232 ^oC rises to 267 ^oC, then the water is boiled and produced steam at the pressure of 53 bar at constant temperature of 267 ^oC.

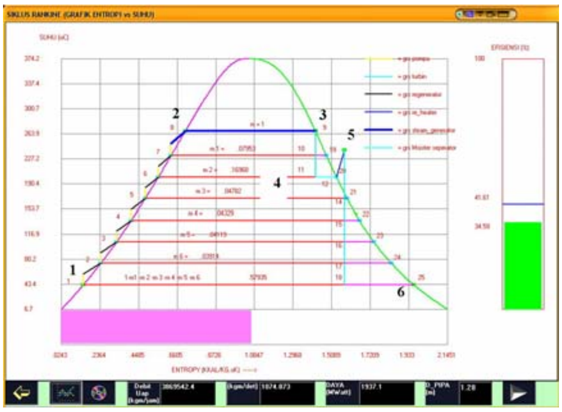


Figure 2. The entropy vs temperature of the NPP Rankine cycle

The high pressure steam at point 3 expands in the high pressure turbine to point 4, where the former temperature of 267 ^oC decreases to 200 ^oC. From point 4 part of steam is heated to point 5 in the reheater, so that the temperature is back to 240 ^oC.

After the reheating process, the steam at point 5 is expanded in the turbine to point 6, the former temperature of 240 ^oC is down to 40 ^oC and becomes vacuum with 0.08 bar pressure. Then the steam is condensed in the condenser from point 6 to point 1 at constant temperature.

Base on that process, the released steam energy changed to the turbine power could be calculated by[2]:

$$E_t = \Sigma\{m_n h_n - m_{(n+1)} h_{(n+1)}\} \quad (1)$$

Where : E_t = the received energy by turbine, m_n = the mass steam fraction of *n-th*, h_n = the steam enthalpy at *n-th*, and n = the amount of regenerator.

The energy received by the steam in the steam generator consists of two groups that are:

1. The received energy from point 2 to point 3

$$E_{s1} = h_3 - h_2$$

where: E_{s1} = the received energy in the steam generator, h_3 = the enthalpy at point 3, h_2 = the enthyalpy at point 2.

2. The received energy from point 4 to point 5

$$E_{s2} = h_5 - h_4$$

where: E_{s2} = the received energy in the reheater, h_5 = the enthalpy at point 5, h_4 = the enthalpy at point 4.

So, the total energy received by the steam is:

$$E_s = E_{s1} + E_{s2} \quad (2)$$

The Rankine cycle efficiency of Figure 2 can be written as:

$$\eta = (E_t - E_p) / E_s \quad (3)$$

where η = the Rankine cycle efficiency, E_p = the pumping energy.

From equation (3), the power which is given by the steam to the generation system is:

$$P = E_t - E_p \quad (4)$$

where : P = power per mass of steam.

From equation (3), the power which is given by the steam generator to the turbine is approximated by:

$$P_{sg} = P_t / \eta \quad (5)$$

where P_{sg} = steam-generator power. This power is produced by the reactor.

From equation (4) and (5), the steam flow rate need of the conversion system is calculated with the formulation of:

$$M_{sg} = P_{sg} / P_m \quad (6)$$

where : M_{sg} = the steam flow rate which is produced by the steam generator.

2.2 The Nozzel Concept

The nozzel concept is based on the open process thermodynamic which gives relationship between enthalpy and velocity of the flow rate, and is expressed by the following equation[2)].

$$h_1 = V_1^2 / 2J = h_2 + V_2^2 / 2J \quad (7)$$

where, h_1, h_2 = the steam enthalpy on point 1 and 2, V_1, V_2 = the velocity on point 1 and 2, J = conversion factor.

The steam enthalpy is the pressure and temperature functions where the value can be picked from the steam table. The steam expansion process in the turbine is assumed as isentropic process expressed in the equation of[2)] :

$$p_1 v_1^{\chi} = p_2 v_2^{\chi} \quad (8)$$

where: p_1, p_2 = the steam pressure at point 1 and 2, v_1, v_2 = the steam specific volume at point 1 and 2, and χ = the steam constant.

Further analysis of equation (7) and (8) gives[3)]:

$$M_t = A.p.F\sqrt{RT} \quad (9)$$

where, M_t = the steam flow rate through the nozzel, A = the inflow nozzel cross-section, p = the inflow nozzel pressure, R = the steam constant, T = the steam temperature.

$$F = \sqrt{\frac{2\chi}{\chi - 1}\left(\frac{po}{p1}\right)^{2/\chi} - \left(\frac{po}{p1}\right)^{\frac{\chi+1}{\chi}}}$$

Through equation 9), the steam flow rate could be determined. On the other hand, if the flow rate is known, the nozzel cross-section can be calculated. Both conditions are applied in the simulation process.

2.3 The valve concept

The valve concept is based on ISA standard (Instrument Society of America). For valve size determination, this equation is used[4)]:

$$W = N_6.F_p.C_v.Y\sqrt{x.p_1.\gamma_1} \quad (10)$$

where: W=the valve flow rate, N_6 = 27.3, C_v = the valve constant, $x = \Delta p/p_1$, p_1 = the steam pressure, γ_1 = the steam mass specification, F_p = the pipe geometric factor, $F_k = \chi/1{,}4$, $Y = 1 - x / (3F_k X_T)$, XT = clamp factor.

The cross-section area of the valve is determined by the Cv valve value and the valve type according to the valve data. The x, Cv, and Y value have non linear correlation where the solution needs trial and error calculation, so that the derivation program is necessary.

3. Computer Code

The computer code consists of three codes. The first code is the simulator, the second is Rankine cycle, and the third is flow animation. The simulator is the only code then can be described.

The code is directed to read the input data coming from the data file, and then is executed, where the result is used as the rated value. This process produces values, among other things are the valve size, the cross section nozzel size, and the cycle efficiency.

The data execution consists of the data reading process, the Rankine cycle efficiency calculation with six regenerators, the steam mass flow rate, the valve size calculation with ISA standard, and the nozzel cross-section area calculation.

These values are displayed on the monitor besides the pressure and the temperature from any positions. After this process, the code is directed to reduce the turbine power to an arbitrary percentage value. During the power degradation process, the changing value is displayed on the monitor.

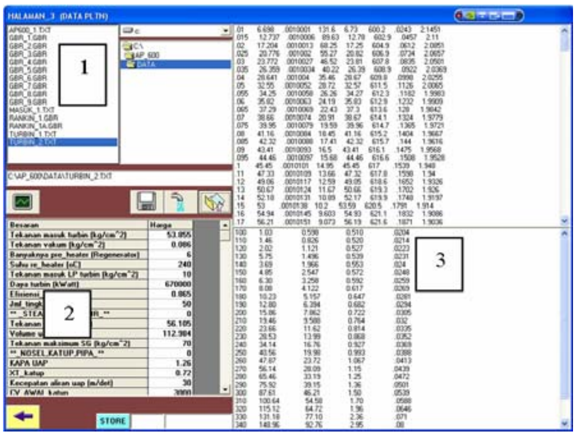
During the power degradation process, the dump valve or the safety valve can be forced in to the malfunction condition, so that the steam generator pressure achieves safety limit. In this condition, the alarm will be initiated, and the software will produce a special sound. The result of some units is recorded on a list box and can be evaluated after the end of the processes.

4. Results and Discussions

In this paper all pages of the computer code are viewed and discussed. The first page to discussed is the data file which is displayed on Figure 3.

Box number 1 is a file box where the data are saved in a unique name, and consist of a Drive box, a Directory box, and a File List box. In this box, the data can be saved, and the saving data file can be searched, and the contents are transferred to Box 2.

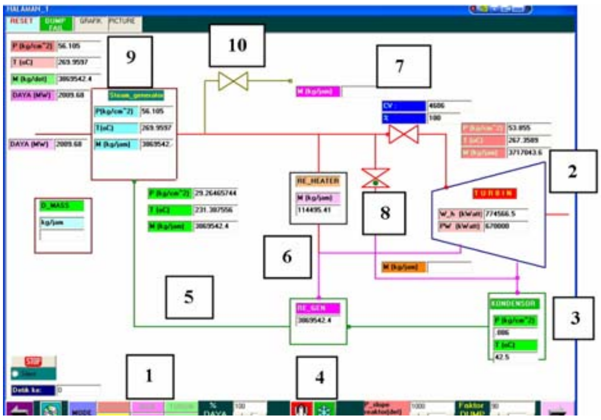
Box 2 is constructed of MSFlexGrid box which has two columns and eighteen rows. The first column is used for unit name, and the other is used for unit values. There are 18 data information which are used as the input data, both for the simulator process and for the Rankine cycle process. Box 3 is used for steam data storage which is read during the simulator process or Rankine cycle process.



1=file box, 2=data and values, 3 = steam data

Figure 3. Data file page

The second page is the simulator page where the process and the changing values are displayed.



1=mode operation selection, 2=turbine, 3=condenser, 4 = regenerator (representative), 5=feed water line, 6=reheater, 7=control valve, 8 = dump valve, 9 = steam generator, 10 = relieve valve

Figure 4. Simulator page

After the data in page 1 is transferred to the MSFlexGrid box, then page 2 can be opened. During the opening process of page 2, the block diagram is drawn as seen on Figure 4.

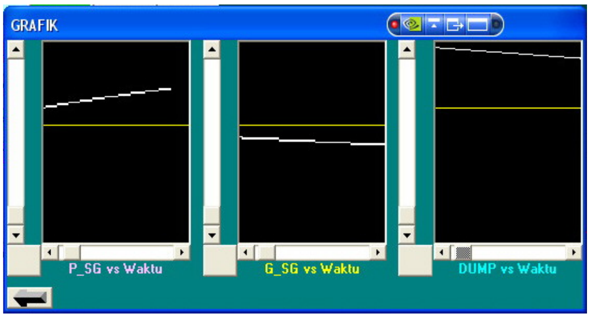
The next processes are the mode selection process and the value arrangement process which are placed on Box 1. In the arrangement process, the values of the turbine power percentage, mass dump percentage, and the steam generator power gradation can be arranged. In the mode selection process, either the turbine or the reactor can be selected.

After the mode selection and the arrangement, then the code can then be executed, and the result on every step is displayed. In Box 2 (turbine), the power, pressure, and the temperature are displayed; in Box 3 (condenser), the vacuum and the temperature are displayed. In Box 4 (regenerator) and Box 5 (feed water line), the water flow rate, and the temperature are displayed.

The important things are the pressure, temperature, and the steam production in the steam generator. During the turbine power reducing processes, the steam production and the steam outflow are in imbalance condition. Where the steam production is greater than outflow, the steam generator pressure will go up slowly.

In normal condition, the highest pressure of the steam generator is still in the safe condition. Unfortunately, in the steam dump malfunction, the steam generator pressure will be higher than the safety condition. In this event, the alarm will be initiated, and the sound is beep.

During the process, the steam generator pressure, the steam generator mass production, and the mass dump are displayed in three picture boxes. These picture boxes can be viewed by clicking the icon in the upper side of the page and are displayed in Figure 5.



P_sg=steam generator pressure, G_sg=mass production of steam generator Dump = mass dump

Figure 5. Graphical for P_sg v.s Time, G_sg vs Time, and Dump vs Time

This computer code is developed by using Basic language and compiled by Visual Basic 5[4].

5. Conclusions

This simulator code can be used for showing the changing values during the steady and the transient condition. This means that the code can also be used for learning the energy conversion process in the nuclear power plant. The Rankine cycle code which is the part of this code can be used for efficiency and steam necessity calculation, so that this code can be used for turbine design process.

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