STUDY ON DISCHARGE HEAT UTILIZATION OF 250 MWe PCMSR TURBINE SYSTEM FOR DESALINATION USING MODIFIED MED

Andang Widi Harto, Atinna Paramita Gunawan
Department of Physical Engineering, Faculty of Enginerring,
Gadjah Mada University Yogyakarya Indonesia 55281,
Email: andangftn@yahoo.com,

Diterima editor 05 November 2012
Disetujui untuk publikasi 17 Desember 2012

ABSTRACT

STUDY ON DISCHARGE HEAT UTILIZATION OF 250 MWe PCMSR TURBINE SYSTEM FOR DESALINATION USING MODIFIED MED. PCMSR (Passive Compact Molten Salt Reactor) is one type of Advanced Nuclear Reactors. The PCMSR has benefit charasteristics of very efficient fuel use, high safety charecteristic as well as high thermodinamics efficiency. This is due to its breeding capability, inherently safe characteristic and totally passive safety system. The PCMSR design consists of three module, i.e. reactor module, turbine module and fuel management module. Analysis in performed by parametric calculation of the turbine system to calculate the turbine system efficiency and the hat available for desalination. After that the mass and energi balance of desalination process are calculated to calculate the amount of distillate produced and the amount of feed sea water needed. The turbine module is designed to be operated at maximum temperature cycle of 1373 K (1200 ºC) and minimum temperature cycle of 333 K (60 ºK). The parametric calculation shows that the optimum turbine pressure ratio is 4.3 that gives the conversion efficiency of 56 % for 4 stages turbine and 4 stages compressor and equiped with recuperator. In this optimum condition, the 250 MWe PCMSR turbine system produces 196 MWth of waste heat with the temperature of cooling fluid in the range from 327 K (54 ºC) to 368 K (92 ºC). This waste heat can be utilized for desalination. By using MMED desalination system, this waste heat can be used to produce fresh water (distillate) from sea water feed. The amount of the destillate produced is 48663 ton per day by using 15 distillation effects. The performance ratio value is 2.8727 kg/MJ by using 15 distillation effects.

Keywords: PCMSR, discharged heat, MMED desalination

ABSTRAK

STUDI PENGGUNAAN KALOR BUANGAN DARI SISTEM TURBIN PCMSR BERDAYA 250 MWe UNTUK DESALINASI MENGGUNAKAN METODE MED TERMODIFIKASI. *PCMSR (Passive Compact Molten Salt Reactor) merupakan salah satu tipe dari Reaktor Nuklir Maju. PCMSR memiliki keuntungan berupa penggunaan bahan bakar yang sangat efisisien, sifat keselamatan tinggi dan sekaligus efisiensi termodinamika yang tinggi. Hal ini disebabkan oleh kemampuan pembiakan bahan bakar, sifat keselamatan melekat serta sistem keselamatan yang secara total bersifat pasif. Desain PCMSR terdiri dari tiga modul, yaitu modul reaktor, modul turbin dan modul pengelolaan bahan bakar. Analisis dilakukan dengan melakukan perhitungan parametrik sistem turbin untuk menghitung efisiensi sistem turbin dan kalor yang tersedia bagi desalinasi. Selanjutnya dilakukan perhitungan neraca massa dan neraca energi proses desalinasi untuk menghitung jumlah distilat yang dihasilkan serta umpan air laut yang dibutuhkan. Modul turbin PCMSR dirancang untuk dapat dioperasikan pada suhu siklus maksimum 1373 K (1200 ºC) dan suhu siklus minimum 333 K (60 ºK). Perhitungan parametrik menunjukkan bahwa perbandingan tekanan turbin yang optimum adalah 4,3 dan memberikan efisiensi maksimum sebesar 56 % dengan menggunakan 4 tingkat turbin serta 4 tingkat kompresor yang dilengkapi dengan rekuperator. Pada kondisi optimum ini, turbin PCMSR dengan daya keluaran 250 MWe menghasilkan kalor sisa sebesar 196 MWth dengan suhu fluida pendingin berkisar dari 327 K (54 ºC) hingga 368 K (95 ºC). Kalor sisa ini dapat digunakan untuk memproduksi air tawar dengan cara desalinasi air laut. Dengan menggunakan sistem desalinasi MMED, jumlah destilat yang dapat dihasilkan adalah 48663 ton per hari dengan menggunakan 15 efek destilasi. Nilai rasio performansi adalah 2,8722 dengan menggunakan 15 efek destilasi.*

Kata kunci: PCMSR, kalor sisa, MMED desalinasi

ISSN 1411–240X
Nomor : 402/AU2/P2MI-LIPI/04/2012

INTRODUCTION

The human energy need is predicted to increase as the increasing of the worldwide human population as well as the requirement for better life. Meanwhile, the conventional energy resources (coal, oil and natural gas) in which has been used to fullfile most of human energy demand recently has been being diminish. Moreover, the uses of the recently conventional power plant accumulate the greenhouse gas. Thus the use of the conventional energy resources must be reduced. Nuclear energy is one of the alternative energy resources that has been proven technologically and economically.

The quantity of the known proven natural uranium by now is 5000 kilo tons [1, 2]. The number of the worldwide nuclear reactor recently is 470 units with the total capacity power of 400 GWe [1]. If the worldwide nuclear energy contribution will be kept constant to the recent power level by using the recent nuclear reactor technology, the worldwide known proven nuclear fuel resources can supply the nuclear power only for 50 until 80 years [1].

The recent nuclear reactor actually utilize the natural fissile U-235 from the whole natural uranium resources. Due to the fact that U-235 is only 0.71 % of mass fraction from total uranium resources, it mean that recent nuclear reactor only utilized less than 1 % nuclear fuel resources (i.e. uranium). More than 99 % of the nuclear material can not be used by the recent nuclear technology. This material ios discharged in the form of depleted uranium and spent fuel. Another potential nuclear fuel resources, *i.e.* thorium still can not be used.

By these reasons, it is urgent to develop innovative nuclear reactor designs to use the nuclear fuel resources for more efficient, to reuse the nuclear wastes and to use the other potential nucler fuel resource, *i.e.* thorium. By the use advanced nuclear reactor with breeder capability, all of the fissile and fertile material can be used. The such reactor can utilize 150 times more efficient in term of natural nuclear fuel resources [3]. It means that the proven uranium and thorium resources known and the wastes from the recent nuclear technology can be used to replace all of the using conventional fuel worldwide for more than 1000 years.

One of the advanced nuclear reactor design is the PCMSR (*Passive Compact Molten Salt Reactor*). PCMSR is designed to use thorium by converting it to U-233. Moreover, the reactor must fulfill safety criteria, i.e. negative power feedback, totally passive safety system and self power regulating capability [4,5].

Another important problem is increasing need of consumed water, whereas the clean water resources gradually diminish in the future. More than 99 % of worldwide water resources is saline water [6]. The fresh water resources such as ground water resources, rivers and lakes are now in gradual reducing quality due to contamination and ecosystem destruction. The increasing of world population and the reducing of fresh water resources will cause fresh water scarcity in the future. In 2025, it is estimated that two third of world population will suffer fresh water splay problem [6] specifically in the area of Africa, Latin America, South Asia and South Asia. Desalination technology promises the solution of fresh water scarcity. Desalination technologies have been developed in Middle East area for fresh water supply. The recent total capacity of desalination is 36 billion m^3 of feed water [6].

However, most of the recent desalination uses energy that primary generated from conventional carbon or hydrocarbon energy resources (coal, oil or natural gas). Increasing desalination capacity in the future will increase environment problem such as global warming if the conventional carbon or hydrocarbon energy resources continually used of desalination.

Thus the alternative and cheap energy source for desalination should be used to overcome the increasing capacity of desalination in the future. The discharged heat from nuclear power plant can be used as cheap energy source for desalination.

FUNDAMENTAL THEORY

PCMSR (Passive Compact Molten Salt Reactor)

Passive Compact Molten Salt Reactor (PCMSR) is one of advanced nuclear reactor design. PCMSR use thorium based fluoride salt. The equilibrium composition of the PCMSR fuel is 29.4 % mole 232ThF4, mole 70 % 7LiF, 233UF4 and the rests are minor actinides and fission products) [7]. PCMSR use graphite as moderator and structure. The mixture of NaF-LiF-KF [8] salt is used as intermediate coolant.

The use of molten salt fuel combined with graphite moderator gives some important benefits, i.e. [9] :

a. The reactor can be operated at very high temperature at low pressure, thus high efficiency of energy conversion meanwhile and elimination of pressure expansion accident probability can be achieved.
b. On line refueling and fuel reprocessing system can be incorporated. This gives benefit to reactor safety due to low excess reactivity as well as simple fuel handling.
c. Pa-233 can be removed from reactor allow it to decays to become U-233. This can increase the reactor breeding capability.
d. The fertile material Th-232 gives strong contribution to achieve relatively large negative temperature coefficient.
e. The resulting of point b, c and d is the possibility to design the reactor core which has inherent safety characteristic, eliminate the probability of power excursion and make the possibility of incorporating the passive shutdown system.
f. The high temperature operation makes the PCMSR can potentially be used as high temperature heat supply system as well as efficient electric power generation. The high temperature heat can be used as many commercial application such as efficient hydrogen production, coal gasification and liquefaction, metal ore reduction etc.

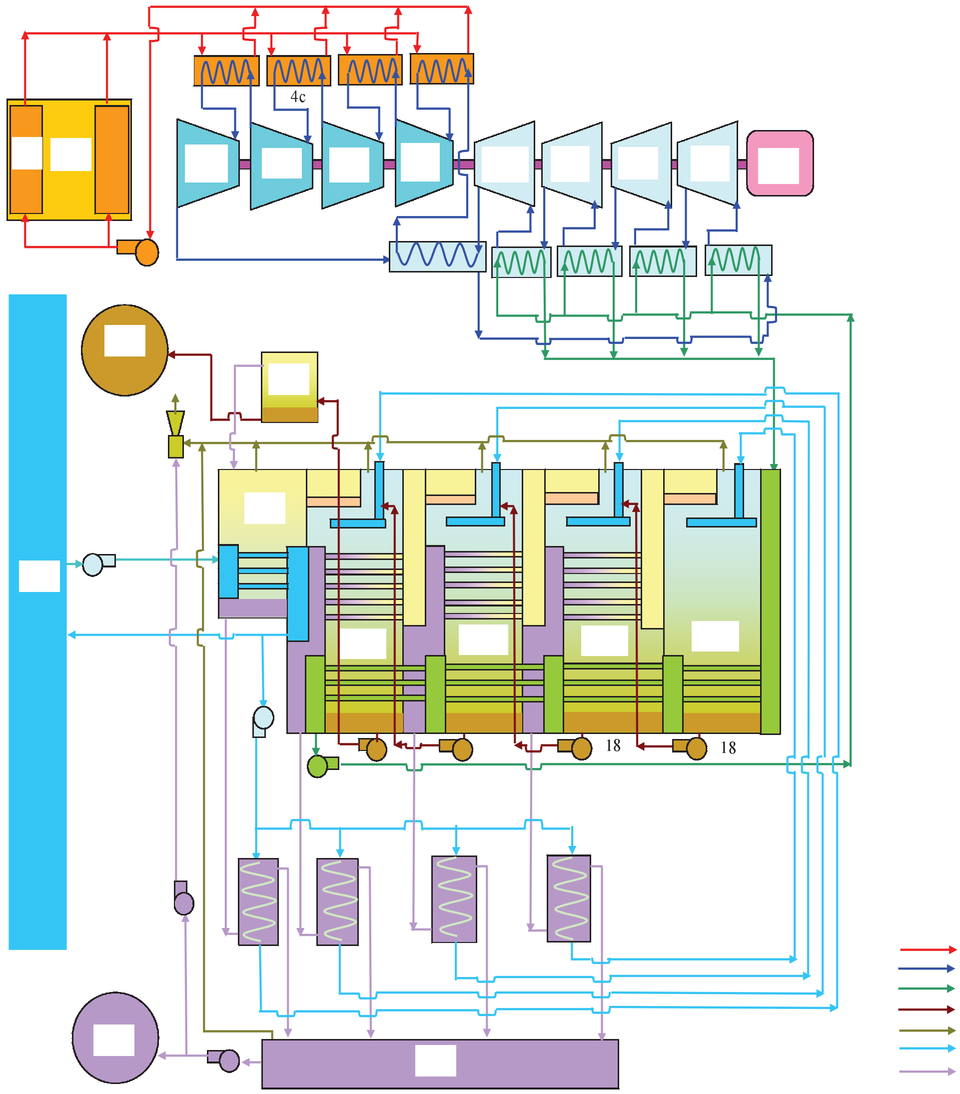
Having breeding capability and applying on line refueling and fuel reprocessing, PCMSR will greatly reduce the cost related to fuel preparation and radiaoctive waste treatment. The next reduction cost of PCMSR is the reduction of capital cost.

Reducing capital cost can be done by simplifiying the design and by reducing construction time period. In PCMSR design, the concept of integral and modularity is applied. All of the components of the system are grouped into several modules. The module consists of several components that have closely related function. Each module is designed so that it can be completely fabricated and tested in a workshop. The module is then completely transported and erected to the powerplant site as constructed. Thus the construction period will be significantly reduced. PCMSR has three main modules, i.e. reactor module, turbine module and fuel management module.

The Turbine Module of PCMSR

Using graphite moderator and very high boiling point of fuel and coolant salt [9], PCMSR is operated at very high temperature. With high temperature, the use of multi heating, multi cooling and regenerating Brayton Cycle gas turbine is more suitable than the use of Rankine cycle steam turbine. Thus the PCMSR uses heating, multi cooling and regenerating Brayton Cycle gas turbine. Figure 1 shows the schematic diagram of the PCMSR turbine system coupled with modified MED desalination system.

ISSN 1411–240X
Nomor : 402/AU2/P2MI-LIPI/04/2012



General Parametric Optimization Of The PCMSR Turbine System

The first step is general parametric optimization of the PCMSR turbine system. The first goal of this calculation is to provide an optimum operation condition that gives maximum energy conversion efficiency at a temperature range suitable with reactor operation temperature. The second goal is to provide the waste heat available for driving the desalination system. The energy conversion efficiency of multi heating, multi cooling and regenerating Brayton cycle can be formulated as :

$$\eta = \frac{\eta_M \eta_L \eta_H \left(N_E \eta_E \frac{T_C}{T_A}\left(1-\left(\frac{1}{\eta_{pE} R_{pE}}\right)^{\frac{\gamma-1}{N_E \gamma}}\right) - \frac{N_C}{\eta_C}\left(\left(\frac{R_{pC}}{\eta_{pC}}\right)^{\frac{\gamma-1}{N_C \gamma}}-1\right)\right)}{\frac{T_C}{T_A}\left(1-\eta_R+\eta_E\left(N_E-1+\eta_R\right)\left(1-\left(\frac{1}{\eta_{pE} R_{pE}}\right)^{\frac{\gamma-1}{N_E \gamma}}\right)\right)-\left(1-\eta_R\right)\left(1+\frac{1}{\eta_C}\left(\left(\frac{R_{pC}}{\eta_{pC}}\right)^{\frac{\gamma-1}{N_C \gamma}}-1\right)\right)+\eta_R\frac{\Delta T_E}{T_A}} \quad (1)$$

where:

η =	Overall efficiency of turbine system	T_C =	Maximum cycle temperature (K)
η_M =	Mechanical efficiency of turbine system	T_A =	Minimum cycle temperature (K)
η_L =	Efficiency of electrical system	ΔT_E =	Bottom regenerator temperature difference (K)
η_H =	Heater efficiency	γ =	Ratio of c_p to c_v
η_E =	Isentropic efficiency of turbine	R_{pE} =	Total turbine pressure ratio
η_C =	Isentropic efficiency of compressor	R_{pC} =	Total compressor pressure ratio
η_{pE} =	Expansion efficiency of turbine	N_E =	Number of turbine stages
η_{pC} =	Expansion efficiency of compressor	N_C =	Number of compressor stages
η_R =	Recuperator efficiency		

The waste heat available for desalination is then can be calculated as:

$$Q_H = \left(\frac{1}{\eta}-1\right)W \quad (2)$$

where:

W =	Turbine system output power (MWe)	Q_H =	Waste heat available for desalination (MWth)

General Calculation of the MMED Desalination

MMED calculation is focused on mass and energy balance calculation. The aim of this calculation is to provide the amount of distillate product per unit input energy for various stage number of desalination.

Mass And Heat Balance of the j^th Effect of Distillation

The mass balance of the jth effect of distillation can be formulated as :

$$\dot{m}_{F,j} + \dot{m}_{B,j-1} = \dot{m}_{B,j} + \dot{m}_{D,j} + \dot{m}_{E,j} \quad (3)$$

$$\dot{m}_{H,j} = \dot{m}_{H,j-1} = \dot{m}_H \quad (4)$$

ISSN 1411–240X
Nomor : 402/AU2/P2MI-LIPI/04/2012

where:

$\dot{m}_{F,j}$	=	Mass flow rate of sea water feed on j^{th} distillation effect (kg/s)
$\dot{m}_{B,j-1}$	=	Mass flow rate of brine outlet from $(j\text{-}1)^{th}$ effect enter the j^{th} effect (kg/s)
$\dot{m}_{B,j}$	=	Mass flow rate of brine outlet from j^{th} effect (kg/s)
$\dot{m}_{D,j-1}$	=	Mass flow rate of distillate outlet from $(j\text{-}1)^{th}$ effect enter the j^{th} effect (kg/s)
$\dot{m}_{D,j}$	=	Mass flow rate of distillate outlet from j^{th} effect (kg/s)
$\dot{m}_{E,j}$	=	Mass flow rate of non condensable gas outlet from j^{th} effect (kg/s)
$\dot{m}_{H,j-1}$	=	Mass flow rate of heating fluid outlet from $(j\text{-}1)^{th}$ effect enter the j^{th} effect (kg/s)
$\dot{m}_{H,j}$	=	Mass flow rate of heating fluid outlet from j^{th} effect (kg/s)

In this case, the heating fluid is the cooling water of the turbine cooler. By assuming that the distillate and the non condensable flow do not contain salt, the mass balance of salt of the jth of can be constructed as:

$$\dot{m}_{F,j}\chi_W + \dot{m}_{B,j-1}\chi_{B,j-1} = \dot{m}_{B,j}\chi_{B,j} \qquad (5)$$

where:

χ_W	=	Salt content of sea water feed (kg salt / kg air)
$\chi_{B,j-1}$	=	Salt content of brine outlet from $(j\text{-}1)^{th}$ effect ((kg salt) / (kg water))
$\chi_{B,j}$	=	Salt content of brine outlet from j^{th} effect ((kg salt)/ (kg water))

The energy balance of the jth effect of distillation can be formulated as :

$$\dot{m}_{H,j}h_{H,j} = \dot{m}_{H,j-1}h_{H,j-1} - Q_{H,j} \qquad (6)$$

$$\dot{m}_{F,j}h_{F,j} + \dot{m}_{B,j-1}h_{B,j-1} + Q_{H.j} + Q_{D.j} = \dot{m}_{B,j}h_{B,j} + \dot{m}_{D,j}h_{D,j} + \dot{m}_{E,j}h_{E,j} \qquad (7)$$

$$Q_{D.j} = \dot{m}_{D,j-1}\left(h_{D,j-1} - h_{D,j}\right) \qquad (8)$$

$$Q_{H,j} = \dot{m}_{H,j}\Delta T_{H,j} \qquad (9)$$

where:

$h_{H,j-1}$	=	Entalphi of heating fluid outlet from $(j\text{-}1)^{th}$ effect enter the j^{th} effect j (kJ/kg)
$h_{H,j}$	=	Entalphi of heating fluid outlet from j^{th} effect (kJ/kg)
$h_{F,j}$	=	Entalphi of sea water inlet at j^{th} effect (kJ/kg)
$h_{D,j-1}$	=	Entalphi distillate product outlet from $(j\text{-}1)^{th}$ effect (kJ/kg)
$h_{D,j}$	=	Entalphi distillate product outlet from j^{th} effect (kJ/kg)
$h_{B,j-1}$	=	Entalphi brine outlet from $(j\text{-}1)^{th}$ effect enter the j^{th} effect j (kJ/kg)
$h_{B,j}$	=	Entalphi brine outlet from j^{th} effect (kJ/kg)
$h_{E,j}$	=	Entalphi non condensable gas outlet from j^{th} effect (kJ/kg)
$Q_{H,j}$	=	Heat transferred at auxiliary heater of j^{th} effect (kW)
$Q_{D,j}$	=	Heat transferred by distillate outlet of $(j\text{-}1)^{th}$ effect distillator (kW)
$\Delta T_{H,j}$	=	Temperature difference of the heat source fluid as pass the j^{th} effect (K or ºC)

The MMED system in this case is designed to has equal temperature difference for each effect. This temperature difference can be calculated as :

$$\Delta T_{effect} = \frac{T_{\max} - T_{\min}}{N_{effect} + 1} \tag{10}$$

where:

ΔT_{effect} = Inter effect temperature diffference (K or ºC)

$T_{\max}$ = Maximum temperature of desalination system (first effect temperature) (K or ºC)

$T_{\min}$ = Minimum temperature of desalination system (condenser temperature) (K or ºC)

N_{effect} = Number of effect

Mass And Heat Balance of Final Brine Flasher

Final brine flasher is used for flashing the brine produced by the last effect. This flashing will give additional amount of distillate. The total mass balance, salt mass balance and energy balances of the final brine flasher can be formulated as :

$$\dot{m}_{B,N} = \dot{m}_{D,N+1} + \dot{m}_{B,N+1} \tag{11}$$

$$\dot{m}_{B,N}\chi_{B,N} = \dot{m}_{B,N+1}\chi_{B,N+1} \tag{12}$$

$$\dot{m}_{B,N}h_{B,N} = \dot{m}_{D,N+1}h_{D,N+1} + \dot{m}_{B,N+1}h_{B,N+1} \tag{13}$$

where :

$\dot{m}_{B,N}$ = Inlet brine flow rate from the last effect (kg/s)

$\dot{m}_{D,N+1}$ = Outlet distillate flow rate of the final brine flasher (kg/s)

$\dot{m}_{B,N+1}$ = Outlet brine flow rate of the final brine flasher (kg/s)

$\chi_{B,N}$ = Salt content of inlet brine from the last effect ((kg salt)/(kg water))

$\chi_{B,N+1}$ = Salt content of outlet brine flow rate of the final brine flasher ((kg salt)/(kg water))

$h_{B,N}$ = Entalphi of inlet brine from the last effect (kJ/kg)

$h_{D,N+1}$ = Entalphi of outlet distillate of the final brine flasher (kJ/kg)

$h_{B,N+1}$ = Entalphi of outlet brine of the final brine flasher (kJ/kg)

Mass And Heat Balance of Condenser

Condenser is used to condensate the distillate produced by the final effect. The condenser uses sea water as coolant. Large part of the sea water after passing through condenser is discharged back to the sea. A small part of the sea water after passing through condenser is used to the desalination feed. The mass balance of condenser can be formulated as :

$$\dot{m}_{D,N} + \dot{m}_{D,N+1} = \dot{m}_{D,C} + \dot{m}_{E,C} \tag{14}$$

$$\dot{m}_{W} = \dot{m}_{S} + \dot{m}_{U} \tag{15}$$

where :

$\dot{m}_{E,C}$ = Non condensable outlet flow rate from condenser (kg/s)

$\dot{m}_{D,N}$ = Distillate flow rate enter condenser from the last effect (kg/s)

$\dot{m}_{D,N+1}$ = Distillate flow rate enter condenser from the final brine flasher (kg/s)

$\dot{m}_{D,C}$ = Distillate outlet flow rate of condenser (kg/s)

$\dot{m}_{W}$ = Total sea water flow rate for condenser cooling (kg/s)

$\dot{m}_{U}$ = Sea water flow rate for desalination feed (kg/s)

$\dot{m}_{S}$ = Sea water flow reat discharged back to the sea (kg/s)

ISSN 1411–240X
Nomor : 402/AU2/P2MI-LIPI/04/2012

The energy balance of condenser can be formulated as :

$$\dot{m}_W h_{W,out} = \dot{m}_W h_{W,in} + Q_S \quad (16)$$

$$\dot{m}_{D,N+1} h_{D,N+1} + \dot{m}_{D,N} h_{D,N} = \dot{m}_{D,C} h_{D,C} + \dot{m}_{E,C} h_{E,C} + Q_S \quad (17)$$

where :

$h_{W,in}$ = Inlet entalphi sea water for condenser cooling (kJ/kg)

$h_{W,out}$ = Outlet entalphi sea water for condenser cooling (kJ/kg)

$h_{D,C}$ = Outlet entalphi of distillate (kJ/kg)

$h_{D,E}$ = Outlet entalphi of non condensable (kJ/kg)

$h_{D,N}$ = Inlet entalphi of distillat from the last effect (kJ/kg)

$h_{D,N+1}$ = Inlet entalphi of distillat from the last brine flasher (kJ/kg)

Q_S = Heat transferred in condenser (kW)

RESULT AND DISCUSSION

General Parametric Optimization of the PCMSR Turbine System

Table 1 shows the general parametric optimization result for 4 stages turbine and 4 stages compressor. The efficiencies of the turbine system is calculated using equation (1) for various values of the turbine inlet temperature. In this calculation, some parameters are assumed to have the values as follows [10] : $\Delta p_{F,regenerator} = 0{,}7$ bar, $\Delta p_{E,regenerator} = 0{,}7$ bar, $p_C = 60$ bar, $T_A = 333$ K, $\eta_C = 88$ %, $\eta_E = 93$ %, $\eta_H = 99{,}9$ %, $\eta_R = 98{,}8$ %, $\eta_M = 99$ %, $\eta_L = 97$ % , $\Delta T_E = 50$ K, $\eta_{pE} = 99{,}3$ %, $\eta_{pC} = 99{,}3$ %.

Tabel 1. Efficiency of multi reheat multi cooling regeneratif Brayton cycle of PCMSR turbine system with turbine inlet temperature of 1373 K as function of the number of stage and turbine pressure ratio (R_{PE})

2 turbine stages and 2 compressor stages		3 turbine stages and 3 compressor stages		4 turbine stages and 4 compressor stages	
R_{PE}	η (%)	R_{PE}	η (%)	R_{PE}	η (%)
1,3745	44,1779	1,9285	52,2499	3,0252	55,4985
1,9645	51,3322	2,4041	54,0122	3,2945	55,7490
2,6568	52,3724	2,9456	54,5503	4,3223	56,1342
3,4511	51,9718	4,2667	54,4986	5,5715	56,1087
4,3474	51,0226	6,8966	53,0824	7,9251	55,6781

Table 1 shows that the overall efficiencies become higher as the maximum temperature (turbine inlet temperature) increases. This case is consistent with the basics thermodynamics theory. At every turbine inlet temperatures, there are maximum values of turbine pressure ratio that gives maximum efficiencies. Due to safety, the maximum fuel temperature of PCMSR is limited to 1473 K. This limitation gives the maximum PCMSR turbine inlet temperature of 1373 K. For PCMSR this operating temperature, the optimum turbine pressure ratio is approximately 4.3 that gives the maximum efficiency of 56 % for the turbine system with 4 turbine stages and 4 compressor stages.

The PCMSR turbine is designed to gives electrical output of 250 MWe. By using equation (2), the waste heat available for desalination can be calculated. The waste heat available for desalination is obtained to be 196 MWth.

General Calculation of the MMED Desalination

The aim of the MMED calculation is to provide the amount of the distillate produced by the MMED desalination system by using the amount of the available waste heat as the energy source. The calculation is generally based on the heat and the mass balance formulated by equation (3) until equation (14). The heat source fluid in this case is the cooling water of the turbine system compressor cooler. The heat source fluid enter the desalination system at the temperature of 368 K (95 ºC) and leaves the desalination system at the temperature of 327 K (54 ºC). The maximum temperature of the desalination system is 360 K (87 ºC) at the first effect. The minimum temperature of the desalination system is 311 K (38 ºC), at the condenser. The salt concentration of the sea water feed is assumed as 30 g of salt per 1 kg sea water [11]. The desalination calculation results for various number of effects is shown by Table 2. Performance ratio is defined as the mass of total distillate produced per unit heat input from the heat source fluid.

Table 2. Calculation result of MMED system using 196 MWth heat source with various number of effects

Number of effect (N_{effect})	Effect tempe-rature difference (ΔT_{effect})	Total distillate product (ton/day)	Perfor-mance ratio (kg/MJ)	Effect multipli-cation factor	Number of effect (N_{effect})	Effect tempe-rature difference (ΔT_{effect})	Total distillate product (ton/day)	Perfor-mance ratio (kg/MJ)	Effect multipli-cation factor
1	24.50 K	7035	0.4151	1.0000	9	4.90 K	32050	1.8921	4.5558
2	16.33 K	10369	0.6118	1.4739	10	4.46 K	35129	2.0728	4.9935
3	12.25 K	13325	0.7878	1.8941	11	4.08 K	38045	2.2460	5.4080
4	9.80 K	16748	0.9882	2.3807	12	3.77 K	40869	2.4126	5.8094
5	8.17 K	19889	1.1736	2.8271	13	3.50 K	43793	2.5840	6.2250
6	7.00 K	23041	1.3602	3.2752	14	3.27 K	45448	2.6830	6.4603
7	6.13 K	26060	1.5384	3.7043	15	3.06 K	48663	2.8727	6.9173
8	5.44 K	29235	1.7251	4.1557					

In the case that the number of effect is one (i.e. Single Effect Distillation = SED), the desalination system is simply consist of one evaporator (i.e. the first effect) and condenser. All of the available heat from the heat source fluid is used to evaporate the feedwater in the first effect. The steam of distillate produced is then condensed in the condenser, thus the heat is dissipated to cooling sea water. If all of the available heat for desalination is utilized, the mass flow rate of the destillate produced can be calculated as the amount of the available heat (196 MWth) divided by the latent heat of evaporation of water (i.e. 2403 kJ/kg, at 40 ºC of saturation temperature). In this case, the destillate produced by SED is 7035 ton per day.

In MMED, the available heat is used for all effect of distillation to produce steam of distillate. However, as the distillate steam is condensed, its heat content is not directly dissipated to the cooling sea water. The latent heat resulting from distillate condensation fron the previous effect is used as the additional heat for the next effect of distilation. It means that in MMED, the same amount of available heat (196 MWth) can be used for several succesive distilate productions before finally rejected to the cooling sea water.

Effect multiplication value is defined as the ratio of distillate mass flow rate produced by MMED to destillate mass flow rate produced by SED. Thus the effect multiplication factor of SED

ISSN 1411–240X
Nomor : 402/AU2/P2MI-LIPI/04/2012

must be one (1). The effect multiplication factor value increases as the number of effect increases. For 15 effects MMED, the effect multiplication value is 6.9. It means that the 15 effects MMED can produce distillate with the mass 6.9 times than mass of water can be evaporated by the amount of heat available for desalitation. This characteristic is the important benefit of both of the MED and the MMED desalination system.

In MED desalination system, the heat from the heat source fluid is utilized only for the first effect. In MMED, the heat from the heat source fluid is utilized for all effect. This is the benefit of the MMED system compared to the MED system. As all of the condensation latent heat from the previous effect are completely utilized by the next effect, the next effect recieves more heat than the previuos effect (i.e. heat from the heat source fluid and the condensation latent heat from the previous effect). The consequence, the next effect can produce more distillate than the previous effect. Table 3 shows the calculation result of the 15 effects MMED using the amount of heat from the heat source fluid of 196 MWth. In this case, the salt content of brine product is assumed as 60 g salt per 1 kg brine.

The heat available for evaporation of a stage is the sum of heat transferred by the heat source fluid at this stage and latent heat of condensation from the previous stage. Table 3 shows that as the higher of the stage, the higher the amount of heat available for evaporation. The higher stage evaporator can be fed by with higher mass flow rate of sea water feed. As the consequence, the higher stage evaporator (lower operation pressure) can produce more distillate than the lower stage evaporator (higher operation pressure).

The brine produced by a stage of evaporator is not directly discharged, but is utilized for the next stage. Thus the total brine product is obtained from the final flasher. The total circulated sea water is similar to the see water needed for condenser cooling. Smaller part of the sea water condenser cooling is then utilized as the desalination feed water. The rest (larger part) of the sea water condenser cooling is discharged back to the sea to dissipate the process heat.

Table 3. Calculation result of 15 effects MMED using 196 MWth waste heat from 250 MWe PCMSR turbine system

Effect	Heat from heating fluid (MWth)	Heat conden-sation from previous effect (MWth)	Heat available for evapo-ration (MWth)	Heating fluid temperature (°C)		Effect Tempe-rature (°C)	Opera-ting pressure (bar)	Feed sea water mass flow rate (ton/day)	Distillate product mass flow rate (ton/day)
				Inlet	Outlet				
1	13.0667		13.0667	94.85	92.08	86.01	0.600	934.31	467.59
2	13.0667	12.3919	25.4586	92.08	89.31	82.70	0.383	1815.09	910.03
3	13.0667	24.2064	37.2731	89.31	86.53	79.40	0.334	2659.38	1331.49
4	13.0667	35.5453	48.6120	86.53	83.76	76.09	0.291	3476.17	1735.77
5	13.0667	46.5047	59.5734	83.76	80.99	72.78	0.252	4282.26	2125.65
6	13.0667	57.1545	70.2212	80.99	78.22	69.48	0.218	5000.02	2505.90
7	13.0667	67.6173	80.6840	78.22	75.45	66.17	0.188	5717.79	2879.14
8	13.0667	77.9635	90.0302	75.45	72.67	62.87	0.162	6520.71	3247.04
9	13.0667	88.2324	101.2991	72.67	69.90	59.56	0.138	7226.31	3611.94
10	13.0667	98.4888	111.5555	69.90	67.13	56.25	0.118	8029.23	3977.10
11	13.0667	108.8199	121.8866	67.13	64.36	52.95	0.100	8637.51	4344.74
12	13.0667	119.2897	132.3564	64.36	61.59	49.64	0.085	9391.77	4717.42
13	13.0667	129.9602	143.0269	61.59	58.81	46.33	0.072	10219.02	5095.52
14	13.0667	140.8525	153.9192	58.81	56.04	43.07	0.060	10948.95	5482.89
15	13.0667	152.0714	165.1381	56.04	53.27	39.72	0.050	11678.88	5881.68
Final flash						36.95	0.043		349.30
Condenser		164.3022				36.95	0.043		

Total distillate product	=	48663 ton per day	Heat content of distillate	=	14.9249 MWth
Total brine product	=	47674 ton per day	Heat content of brine	=	16.6362 MWth
Total feed sea water	=	96537 ton per day	Heat rejected via condenser	=	164.3022 MWth
Total circulated sea water	=	655716 ton per day	Total heat rejected	=	195.8633 MWth
Discharged sea water	=	559179 ton per day	Salt content of brine product	=	60 g salt per kg brine

CONCLUSION

The optimum condition of PCMSR 250 MWe with inlet turbine temperature of 1373 K has been calculated. The optimum turbine pressure ratio is approximately 4.3. This condition gives the maximum efficiency of 56 % and the waste heat of 196 MWth. This waste heat can be utilized for sea water desalination using MMED desalination system. By using 15 effect of MMED desalination system, the 196 MWth of waste heat can produce 48663 ton per day of fresh water (distillate), with the performance ratio of 2.8727 kg fresh water per MJ of heat input. The effect multiplication value of the desalination system is 6.9173.

REFERENCES

1. Anonim. Uranium Resources and Nuclear Energy 03 Dec 2006 pdf, Energy Watch Group, EWG Paper No 1-06; 2006
2. Anonim. US Geological Survey, Mineral Commodity Summaries (1997-2006); 2006
3. Harto AW. Fuel burp up calculation of Passive Compact Molten Salt Reactor (PCMSR) with on line fuel reprocessing for very long time operation. The 3rd Asian Physics Symposium 2009 (APS 2009), Bandung; 2009. p. 397-402.
4. Noha IN, Harto AW, Sihana. Analisis pengendalian daya reaktor PCMSR dengan pengaturan laju aliran pendingin. Jurnal Teknologi Reaktor Nuklir Tri Dasa Mega. 2012; 14, 2: 91-107
5. Imron M, Harto AW, Sihana. Analisis transient Passive Compact Molten Salt Reactor (PCMSR). Jurnal Teknologi Reaktor Nuklir Tri Dasa Mega. 2010; 12, 2: 73-90
6. Anonim. Economics of nuclear desalination: new developments and site specific studies; 2007, Tecdoc. IAEA No.1561, Vienna.
7. Harto AW. Passive Compact Molten Salt Reactor (PCMSR), modular thermal breeder reactor with totally passive safety system. The 3rd International Conference on Advances in Nuclear Science and Engineering 2011 (ICANSE 2011), Denpasar; 2011. p. 83-96
8. Benes O, Cabet C, Delpech S, Hosnedl P, Ignatiev P, Konings R, Lecarpentier D, Matal O, Merle-Lucotte E, Renault C, Uhlir J, Aseessment of Liquid salts for Innovative Application ALISIA Deliverable (D-50), Review Report on Liquid Salts for Various Applications, 2009
9. Forsbeg CW, Peterson PF., Zhao HH, An advanced Molten salt Reactor Using High Temperature Reactor Technology, ICAPP.2004.MSR.Paper, 2004 International Congress on Advanced in Nuclear Power Plants (ICAPP '04) Embedded International Topical Meeting, 2004 American Nuclear Sociaty Annual Meeting, Pittsburgh, Pennsylvania, 2004.
10. Harto AW, Optimasi Sistem Turbin Passive Compact Molten Salt Reactor, Jurnal Teknologi Reaktor Nuklir Tri Dasa Mega Volume 10, No. 2, Juni 2008, 2008, p. 80-90
11. Anonim, Optimization of the Coupling of Nuclear Reactor and Desalination System, Tecdoc. IAEA No.1444, Vienna, 2005