Brayton-Rankine Total Energy Space Dynamic Power System Analysis

By

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Abstract : A study is made on combined Brayton-Rankine total energy space dynamic power system. Thermodynamic analysis and comparative calculation are performed for such system and the regenerative Brayton system. Results show that under the space condition even with water as the working medium of the Rankine part the thermal efficiency could be raised at least by 5-10 % at working point in comparison with regenerative Brayton system and much more than the simple Rankine system for the existed technology. The only increase of steam turbine and pump in comparing with regenerative Brayton system will bring no greater effect on system weight consideration. Through radiater area analysis the suggested total energy system shows no sharp increase in radiation area and the spray radiater is more suitable for this purpose. Further conceptional projective study is worth to proceed on with the selection of more optimum parameters and appropriate working substance together with the spray radiater-condenser design considerations.

1. INTRODUCTION

For near future space exploration and utilization purpose, space station dynamic power systems with power range of half hundred to several hundreds of kilowatts are required and it is meaningful to carry on conceptional projective study and design considerations for such system from present. Such dynamic power system study has been concentrated on solar and radioisotope energy source with photovoltaic conversion or thermal conversion. Brayton, Rankine, Stirling power system [1-10] as well as solar voltaic-heat engine combined system [11] and binary mercury Rankine system [12] are studied and reported in the literature.

The comparison and selection of the system is commonly based on energy efficiency, specific weight and radiater area as well as durability, reliability considerations and at the same time balancing with the technological experience and risk involved.

From energy utilization point of view, two optimization trends are applicable to space dynamic power system consideration. One is to effort on approaching more to ideal Carnot cycle, so the upper cycle maximum temperature and the lower rejection temperature as well as the compression, expansion, heating and cooling process should be well organized. The loss existed isentropic compression and expansion process by turbomachinery is nowadays more efficient and experienced. The heating process by solar receiver storage system or radioisotope system is better to cycle efficiency if the working medium starts heating with higher initial temperature. The exhaust cooling process could be optimized to efficiency if it could be taken place with lower constant temperature. On the other hand, from thermodynamic point of view the availability of the input energy should also be well utilized in the space condition. If the exhaust heat rejection temperature could be to more extent close to space surrounding temperature, the energy utilization coefficient or the availability efficiency of the system will be higher as expressed by the 2nd law of thermodynamics. This includes power as well as heat load utilization. The above points dictates the importance of total energy utilization concept in space dynamic power system considerations.

The process and living heat load supply is not yet clear in future space stations. So cogeneration of power and heat in space power dynamic system is the subject of next study. However the cycle or system study based on total energy concept is worth to pay attention since it really brings profitable effect in terrestrial power systems and may even be more important in space applications as the space thermodynamic condition is more attractave to efficient utilization of availability of input energy.

Present simple Brayton or Rankine power systems performance analysis, especially the parametric selection is more or less influenced by the radiater area and weight considerations. Brayton system has the merit of attending higher initial temperature because of using gas working medium. Rankine system inherits the advantage of exhasting waste heat in phase condensation flow with constant temperature. Such two process if combined or topping on one to the other and to develop spray radiator to combine the condensation with radiation in lower temperature with compact structure, the input energy and its avaiilability could be totally well utilized.

In this situation, suggestion of combined Brayton-Rankine total energy space dynamic power system (BRDPS) is considerd here and general thermodynamic analysis and comparison with existed published results of conceptional project study of Regenerative Brayton Solar Dynamic Power System is made. The resuts show clearly the favourability of the suggested total energy space station dynamic power system.

2. POWER SYSTEM THERMODYNAMIC ANALYSIS

Fig.1 is the scheme of Regerative Brayton system and combined Brayton-Rankine system. The T-S diagram of combined system is shown in Fig.2. For comparison purpose the thermal efficiency of the two systems is derived as follows:

1) Simple closed Brayton power system

Let η_{HRS} the efficiency of the thermal heating system, $\tau = T_3/T_1$ the temperature ratio, $\pi = P_2/P_1$ the compressor pressure ratio and is taken nearly equal to the turbine pressure ratio, then the efficiency relation could be written as:

$$\eta_{CB} = \eta_{HRS} \frac{\tau\eta_T\left(1-\frac{1}{4}\right)-\frac{1}{\eta_c}(\psi-1)}{\tau-\frac{1}{\eta_c}(\psi-1)-1} \qquad (1)$$

in which η_T, η_c the gas turbine and compressor efficiency, respectively and $\psi = \pi^{\frac{K-1}{K}}$.

2) Regenerative closed Brayton power system

The heat exhausted in the Brayton cycle is partly returned to the heating of

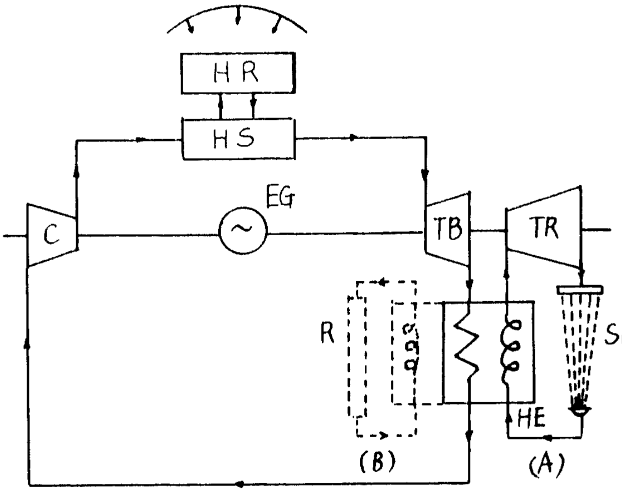

Fig. 1. Scheme of (A) Bryton-Rankine combined power system and (B) regenerative Brayton power system HR-Solar heat receiver HS=heat stotrage C=Compressor EG=Electric generator T_R=Bas turbine T_R=Vapour turbine HE=Heat exchanger SR=Sparay radiater R=Radiater

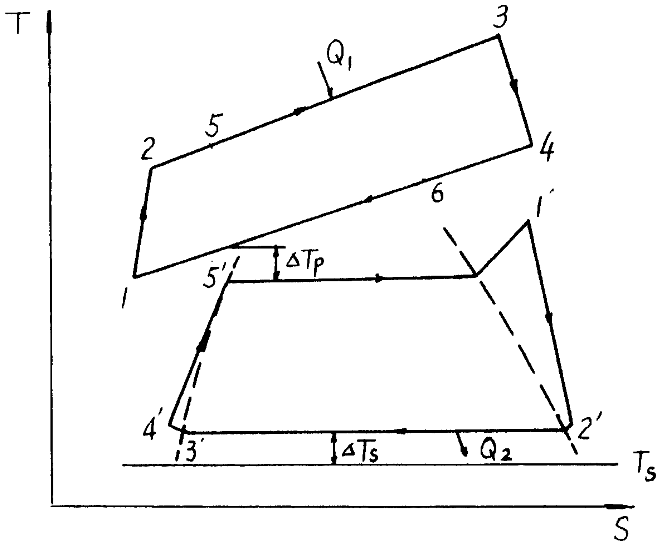

Fig. 2. T-S diagram of Brayton-Rankine combined power system

compressed gas through recuperator. If the ideal regenerative effect is denoted by E

$$E'=\frac{\dot{i}_{5c}-\dot{i}_2}{\dot{i}_4-\dot{i}_2}$$

the thermal efficiency of regenerative closed Brayton power system could be derived as

$$\eta_{RCB}=\eta_{HRS}\frac{\tau\eta_T\left(1-\frac{1}{4}\right)-\frac{1}{\eta_c}(\psi-1)}{(1-E)\left[\tau-\frac{1}{\eta_c}(\psi-1)-1\right]+E\eta_T\tau\left(1-\frac{1}{4}\right)} \qquad (2)$$

3) Combined Brayton-Rankine power system

The thermal efficiency is defined as:

$$\eta_{CBR}=\eta_{HRS}\frac{(W_T-W_C)+(W_T'-W_P')\cdot m}{Q_1}$$

where $m=G_R/G_B$ is the mass flow rate ratio of Rankine part to Brayton part, W_P is the work of pump which is neglected in the following analysis as its value is relatively small. For ease of analysis, the above definition could be rewritten as:

$$\eta_{CBR}=\eta_{SCB}+\eta_{HRS}\frac{mW_T'}{Q_1}=\eta_{SCB}+\eta_{CR}' \tag{3}$$

in which η_{SCB} is the simple Brayton cycle efficiency represented by eq.(1), η_{CR}' is the thermal efficiency of Rankine part that bottoming the Brayton part. The Rankine part of the system depends strongly on the parameters of the Brayton part and also itself and should be matched in parameters selection in order to fulfil heat ballance and other conditions and achive optimized efficiency.

In the following derivation of η_{CR}', it is assumed: (1) The space surrounding temperature T_S is assumed to be a known constant and the Rankine waste heat rejection temperature $T_S+\varDelta T_S$ in which $\varDelta T_S$ is to be selected.

(2) Vapour in Rankine turbine expands to the saturation temperature $T_2'=T_S+\varDelta T_S$ and the temperature rise in pumping is negligible so it could be assumed $T_4'=T_S+\varDelta T_S$.

(3) The Brayton exhaust heat is wholly used to heating the Rankine working medium from saturation to superheating state. In this process the unavoidable pinch point temperature difference $\varDelta T_P$ is necessary to keep a minimum constant. The mass flow rate ratio m and the maximum initial temperature of Rankine part T_1' is determined by the heat balance relations.

(4) For the space dynamic power system the Brayton maximum initial temperature T_3 is usually determined from energy source capability, strength material, durability and reliability considerations, so all the other temperature parameters are reduced to the ratio with T_3.

(5) The specific heat at constant pressure C_P for gas, liquid and vapour phase is assumed to be constant in the selected temperature and pressure range.

(6) Simplification is made in the analysis that the heating process for liquid and vapour state in Rankine part and the cooling process in Brayton part are represented by linear slope in the T-Q diagram as shown in Fig.3. The slope value is $1/G_iC_{Pi}$ respectively.

Under the above consideration, from the heat balance between two parts (see Fig. 3) it could be derived,

$$G_BC_{PB}(T_4-T_1)=G_R[C_{PRL}(T_5'-T_4')+L+C_{PRV}(T_1'-T_5')] \tag{4}$$

or reduced in dimensionless form

$$m=\frac{C_{PBRL}\left[1-\eta_T\left(1-\frac{1}{\psi}\right)-\tilde{\tau}\right]}{C_{PRSL}\,\tilde{\tau}_1+\tilde{L}+\tilde{\tau}_5'[1-C_{PRSL}]-\tilde{\tau}_4'} \tag{4'}$$

Besides, the following relations could be deduced from Fig.3,

$$T_4-T_1'=\frac{G_R}{G_BC_{PB}}\frac{[L+C_{PRS}(T_1'-T_5')]}{\eta_E}-[T_1'-T_5']-\varDelta T_P \tag{5}$$

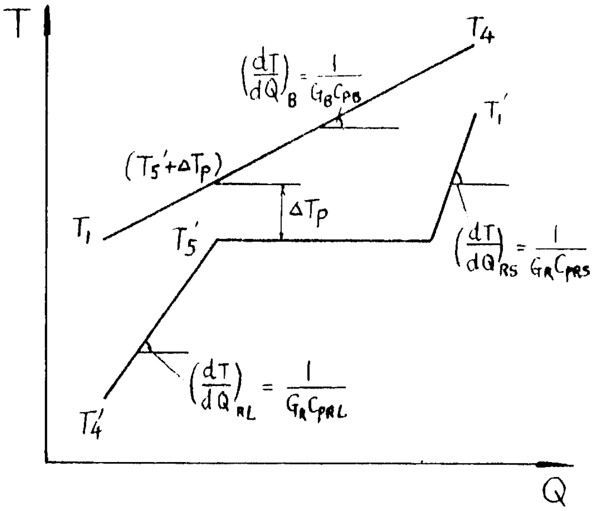

Fig. 3. T-Q diagram of the heat exchanger process in Brayton-Rankine combined power system

or

$$\tau_1' = \frac{C_{PBRS}\eta_E}{m}\left[1-\eta_T\left(1-\frac{1}{\psi}\right)-\varDelta\tilde{\tau}_P\right]-\frac{\tilde{L}}{C_{PRSL}}-\left(\frac{C_{PBRS}\eta_E}{m}-1\right)\tilde{\tau}_5' \qquad (6')$$

Similarly at the initial heating stage of T_4' to T_5', we have

$$T_1 = \varDelta T_P + \left(1-\frac{m}{C_{PBRL}\eta_E}\right)T_5' + mT_4' \qquad (7)$$

or

$$\tilde{\tau}_1 = \varDelta\tilde{\tau}_P + \tilde{\tau}_5'\left(1-\frac{m}{C_{PBRL}\eta_E}\right) + \tilde{\tau}_4'\frac{m}{C_{PBRL}\eta_E} \qquad (7')$$

The three unknowns of the combined Brayton-Rankine combined power system T_1, T_1' and m are then possible to be solved from the above equations under every Brayton part variable t and π.

Finally the thermal efficiency of Brayton-Rankine combined power system could be written from eq. (3),

$$\eta_{CBR} = \eta_{CB} + \eta_{HRS}\eta_T'\frac{m}{G_{BRS}}\frac{(\tilde{\tau}_1'-\tilde{\tau}_4')}{\left(1-\frac{\psi-1}{\tau\eta_c}-\frac{1}{\tau}\right)} \qquad (3')$$

The saturation temperature T_5' and its corresponding pressure P_5' could be selected depending on system efficiency and working medium considerations. Obviously this should be compromised between efficiency and structure-material consideration. It could be seen from the equation that the combined total energy system is dependent on m and T_1' which is in turn functions of τ and π of the Brayton part as well as the T_5' and its heat of vaporization L of the Rankine working medium.

3. CALCULATION RESULTS AND COMPARISON

The relations in preceding paragraph is calculated numerically and the results are shown in Fig.4-11. For the space station Brayton power system the working medium is taken as $A_r - X_e$ mixture, the same as in the examples of [8] and [9]. The specfic heat ratio K = 1.667 for mixture of 71.8% A_r and 28.2% X_e. The working medium

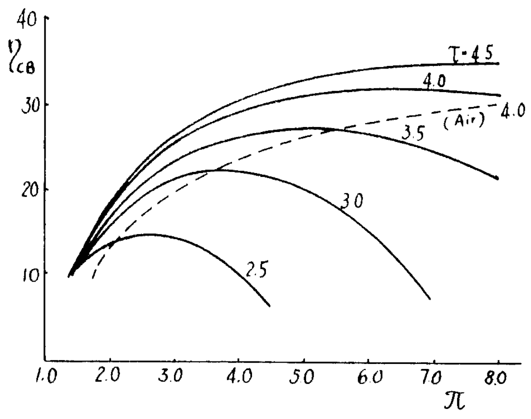

Fig. 4. Thermal efficiency of simple Brayton power system

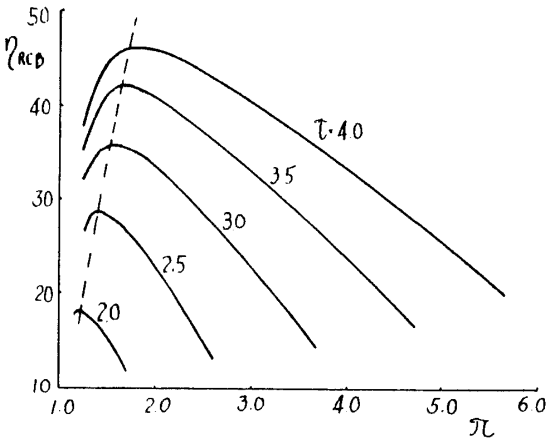

Fig. 5. Thermal efficiendy of regenerative Brayton power system ($E=0.9$)

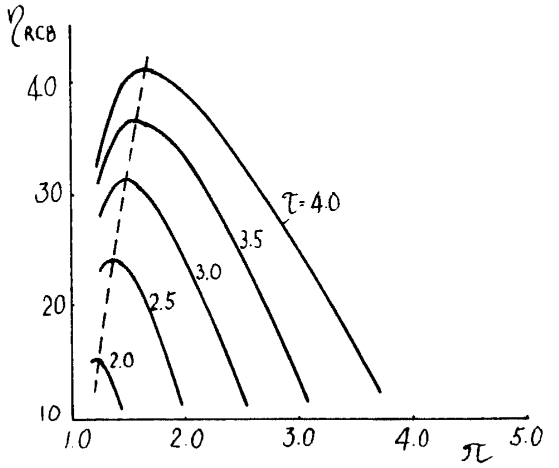

Fig. 6. Thermal efficiency of regenerative Brayton power system ($E=0.85$)

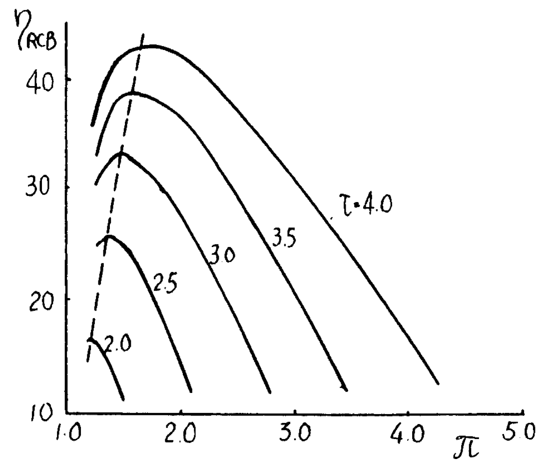

Fig. 7. Thermal efficiency of regenerative Brayton power system ($E=0.8$)

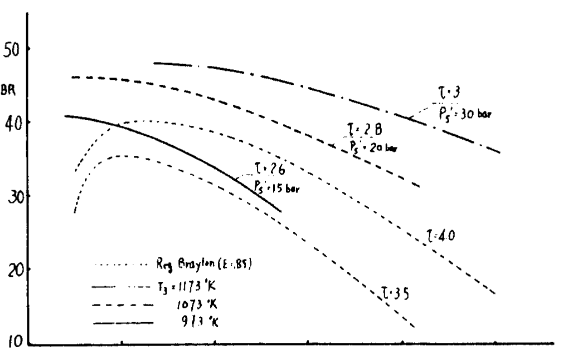

Fig. 8. Thermal efficiency of Brayton-Rankine combine power system ($T=36$ °C)

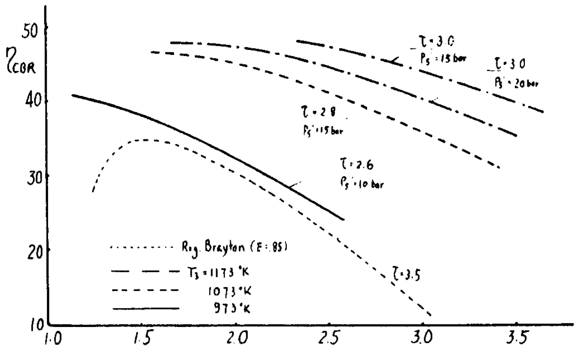

Fig. 9. Thermal efficiency of Brayton-Rankine combined power system ($T=60$ °C)

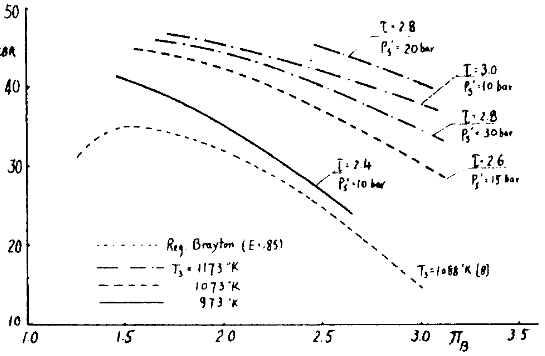

Fig. 10. Thermal efficiency of Brayton-Rankine cobined power system ($T = 100$ °C)

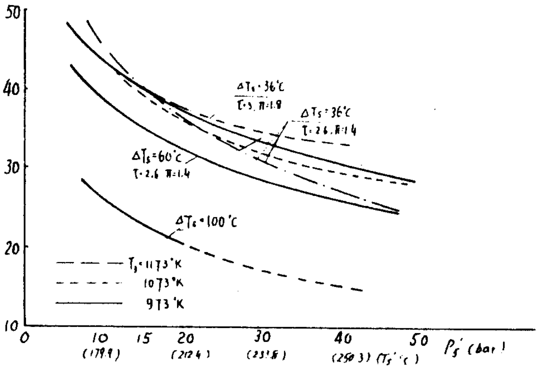

Fig. 11. Variation of thermal efficiency of Brayton-Rankine combined power system with vaporization temperature and pressure

of Rankine part is primarily selected to be water since the temperature range is appropriate for it and it is also stable and easy to handling. Tab.1 lists the main data for efficiency calculation and comparison:

Tab. 1

Gas turbine inlet temperature °K)	T_3	973 (1073,1173)
Brayton gas specific heat (Kcal/kg°C)	C_{PB}	0.9021
Ratio of specific heat of water	C_{PRVL}	2/3
Pinch point temp. difference (°K)	T_P	15
Space surrounding Temperature (°K)	T_S	227
Gas and vapour turbine efficiency		0.88
Compressor efficiency		0.85

In reference [8] and [9] are reported detail conceptional project study results of Solar regenerative closed Brayton power system. Some main data of the power system calculation is re-listed here in Tab.2 for comparison:

Tab.2

	[8]		[9]	
Rated power N (KW_e)	25		11	
Brayton T_3,P_3 (°K,bar)	1088	2.99	973	6.57
Gas turbine exhaust T_4, P_4 (°K,bar)	941	1.95	823.7	4.60
Regenerator outlet T_6, P_6 (°K,bar)	445	1.93	387.6	4.02
Compressor inlet T_1, P_1 (°K,bar)	333	1.92	282.7	3.94
Compressor outlet T_2, P_2 (°K,bar)	419	3.07	368.5	6.89
Regenerator outlet T_5, P_5 (°K,bar)	915	3.02	803.7	6.81
Brayton temperature ratio	3.267		3.442	
Compressor pressure ratio	1.599		1.74	
Proposed radiater specific area A_B/N (m^2/KW)	1		6.2	

Fig.4 is the simple Brayton cycle thermal efficiency for different τ and π . It is also the regerative Brayton cycle thermal efficiency when E = 0. The $A_r - X_e$ gas achieves higher efficiency than air ($K = 1.4$) in smaller value of τ . Fig.5-7 is the Regenerative Brayton power system thermal efficiency for different E. It could be seen that optimal pressure range for this working medium is only 1.5-1.75 for the assumed maximum cycle temperature T_3 and even smaller with decrease of E value.

The thermal efficiency of combined Brayton-Rankine total energy power system with respect to τ and π variations and different maximum temperature T_3 under different Rankine condensation temperature is shown in Fig.8-10. The efficiency curve based on parameters of regerative Brayton system given by [8] and [9] are also drawn in the figure for comparison. There should be an optimization of Brayton-Rankine system from more detail calculation and matching but even with the present consideration of the total energy combination, a surpass of 5-10% in selected working point could noticed in comparing with present regerative Brayton system studied example. 5% is at least for T_3 of 973°K and apparently increased to 10% or more if T_3 is 1073°K and higher.

The effect of T_S or the Rankine condensation temperature and the saturation-evaporation temperature T_5' (thus the presure) are representatively shown in Fig 11 -12. With $\Delta T_S=36°\mathrm{K}$ the efficiency could be 4-5% higher than $\Delta T_S=60°\mathrm{K}$. Similarly there exists solution of appropriate or optimal T_5 . So if the relative low rejection temerature compact two-phase condensation-radiater system could be solved, this total energy dynamic power system is very perspective for future developement.

4. RADIATOR AREA ANALYSIS

Regerative closed Brayton power system exhaust the waste heat from the regenerator outlet temperature T_6 to the compressor inlet temperature T_1. The total amount of heat to be radiated is $C_{PB}(T_6-T_1)$ which could be roughly estimated by

$$Q_{2RB}=N_B(1-\eta_{RCB})/\eta_{RCB}$$

The Rankine part in the combined system exhausts the heat of condensation at constant temperation which is lower than the compressor inlet temperature T_1. For the combined system the heat exhasuted and to be radiated is roughly:

$$Q_{2CBR}=N_{BR}(1-\eta_{CBR})/\eta_{CBR}$$

If $N_B = N_{BR}$ then

$$Q_{2BR}/Q_{2RB}=(1-\eta_{CBR})\eta_{RCB}\Big|(1-\eta_{RCB})\eta_{CBR}$$

If $\eta_{CBR}>\eta_{RCB}$, then $Q_{BR}<Q_{RB}$. But on the other hand the heat radiation is dominated by Stephen-Boltzman law and is proportional to T the fourth power. Therefore for better comparison of the radiator area required, the following analysis is made.

For the radiator heat transfer model shown in Fig.12, the quantity of heat transfered through area element dA_i could be written as:

(1) From the working medium to the radiator wall

$$dQ_{GW}=\alpha(T-T_W)dA_i \tag{7}$$

in which α is the heat transfer coefficient from gas to wall (2). From wall to space surrounding by radiation

$$dQ_S=\varepsilon\sigma(T_W^4-T_S^4)dA_R \tag{8}$$

The exhaust waste heat from Brayton and combined Brayton-Rankine system is, respectively:

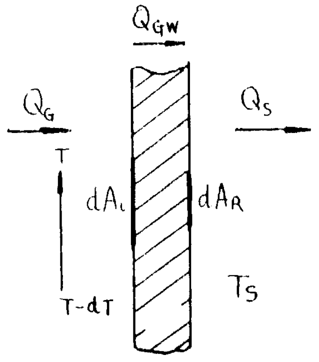

Fig. 12. Radiater heat transfer analysis mode

$$dQ_B = -C_P G_B dT \tag{9}$$

$$Q_R = L G_{BR} \tag{10}$$

In steady process

$$Q_B = Q_{GW} = Q_{SB} \text{ and } Q_R = Q_{SR}$$

For regenerative Brayton exhaust after combining eq.(8),(9) and (11), we get in the following for simplification of analysis, assume $T_W = k_w T$. After integration from T_6 to T_1, the Brayton radiative area per unit working medium mass flow rate is

$$\frac{A_{RB}}{G_B} = \frac{C_{PB}}{4\sigma\varepsilon k_w T_S^3}\left[\left(\ln\frac{T_6 - \frac{T_S}{k_w}}{T_6 + \frac{T_S}{k_w}} + 2\frac{T_6 k_w}{T_S}\right) - \left(\ln\frac{T_1 - \frac{T_S}{k_w}}{T_1 + \frac{T_S}{k_w}} + 2\tan^{-1}\frac{T_1 k_w}{T_S}\right)\right] \tag{12}$$

For Rankine type exhaust the following relation is obtained after combining equation (8) and (10)

$$\frac{A_{BR}}{G_R} = \frac{L}{\varepsilon\sigma T_S^4\left[\left(1 + \frac{\Delta T_S}{T_S}\right)^4 - 1\right]} \tag{13}$$

The numerical calculted results are shown in Fig.13 and 14.

It could be seen that for Brayton system (simple or regenerative), besides the regenerator outlet temperature (or radiater inlet temperature), the radiator area per unit mass flow rate is also increased with the increase of temperature difference between compressor inlet and space surrounding. The efficiency is also very sensible to this temperature at fixed T_3. For the Rankine part, the radiator area is less sensitive to ΔT after the $(T_S + \Delta T_S)/T_S$ ratio is greater the 1.3 or so which represents the value of ΔT_S of 50-60 °C but nevertheless it still influences on the area value. In range of $\Delta T_S = 60°C$ for example the ratio of A_B/A_{BR} is roughly 0.947 in comparing with the example data of (8) and is 0.634 for example data of (9). So it could be said that the radiator area increase for Brayton-Rankine combined system will not exceed 2 times of regenerative Brayton system for $T_3 = 973$ °K and will be more close to it when T_3 is raised to 1073 k or more.

However the most important point is that the condensation exhaust of Rankine part makes possible full use of the advantage of spray type radiator now in develope-

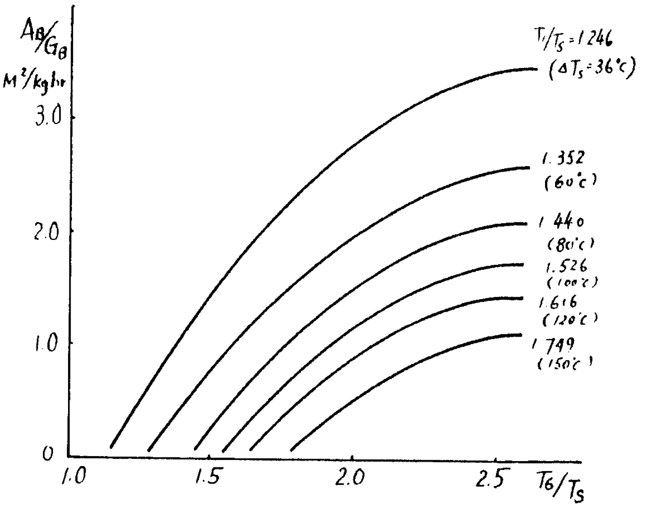

Fig. 13. Variation of radiater specific area with rejection temperature in Brayton Power system

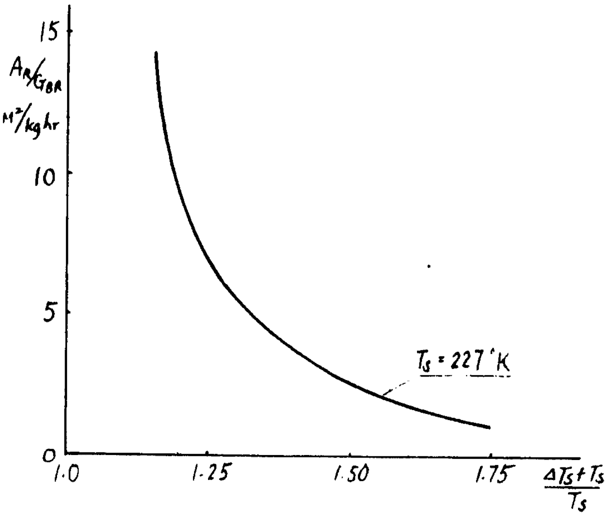

Fig. 13. Variation of specific radiator area with rejection temperature in Brayton-Rankine power system

ment. The condensation process in cooperation with radiation in spray radiator will cause real area increase from droplets and could decrease the power for spraying liquid and it is easier to collect the spray after condensation or even solidization. Moreover the system weight could be decreased by such direct condensation-radiation combination.

5. CONCLUDING REMARKS

Power demand in space station will be increased to more than 10-20 KW to even several hundreds kilowatts in near future space exploration and utilization. Based on the total energy concept, the suggested Brayton-Rankine combined dynamic power system is analyzed and shown to have at least 5-10% increase in efficiency for selected working point in comparing with the existed example of conceptional solar Brayton power system projective study with the present solar system maximum temperature used. The efficiency gain will be more increased with the increase of system maximum heating temperature T_3 and the system is more ready for increased power rating.

Analysis shows also that the Rankine part condensation temperature has important influence on system efficiency. Smaller temperature dfference with the space surrounding will apparently increase the system thermal efficiency and avalabilty utilization but will also cause the increase of radiator area. From analysis and comparison of calculation results with the existed projective study examples, it is noticed that the increase in area could be approached to regenerative Brayton system or not exceed twice through proper management of the system parameters.

Spray type radiator of combination of direct condensation and radiation is considered appropriate for this system. The increase in area by droplets could compensate the reduction of condensation and rejection temperature so as to enabling further increase of the total energy system efficiency.

Based on the above analysis, further study on optimization of parametric selection and matching with the whole dynamic system as well as more appropriate working medium consideration will be proceeded.

NOTATIONS

C_{PB} = specific heat of Brayton gas at constant pressure
C_{PRL} = specific heat of Rankine liquid at constant pressure
C_{PRV} = specific heat of Rankine vapour at constant pressure
$C_{PBRL} = C_{PB}/C_{PRL}$
$C_{PBRV} = C_{PB}/C_{PRV}$
$C_{PRVL} = C_{PRV}/C_{PRL}$
G = mass flow rate kg/hr
i = enthalpy
L = latent heat of vaporization
$L = L/(C_{PBRL} {}^{*} T_3)$
N = rated power of system
P = pressure
Q = quantity of heat
s = entropy
W = work
π = compressor pressure ratio
$\psi = \pi^{(K-1)/K}$
τ = temperature ratio
$\tilde{\tau}_i = 1/\tau_i$

Subscripts
B = Brayton part of system
E = Brayton-Rankine heat exchanger or boiler
HRS = heat receiver and storage

G = gas
p = pinch point
R = Rankine part of system
Rg = regenerator
s = space
W = wall

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