The study on working fluids of airborne power generation system based on Rankine cycle by heat energy

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Abstract. This paper proposed a new concept named airborne power generation system based on Rankine cycle by heat energy, namely, the presented system combined the Rankine cycle with environmental control system in aircraft to recycle the waste heat of engine bleed air with high temperature and generate power. This paper mainly discussed the choosing of optimum working fluid which could apply in the combined power generation system mentioned above when the temperature of the coming bleed air was about 400 degree centigrade.

1. Introduction
The core part of the airborne environmental control system is the refrigeration system, which is used to secure the safety and comfort, guarantee the normal operation of electronic equipment. At present, air turbine refrigeration technology is widely applied to both the advanced civil aircraft and military aircraft [1]. Furthermore, this technology derives from the high-temperature bleed air of the airborne engine. It’s generally accepted that there is much thermal energy contained in the bleed air, and the temperature is roughly 400 degree centigrade under cruising condition. According to the above situation, the part of high-temperature gas have to be cooled preliminary by ram air. This traditional method not only causes the waste of the thermal energy of bleed air, but also threatens the stealth performance seriously due to the use of ram air. Therefore, with the high-speed development of modern aircraft, how to improve traditional aircraft environmental control system reasonably becomes the most urgent ‘thermal problem’.

Under this circumstances, this paper proposed the power generation system by waste heat energy in bleed air based on Ranking cycle. This combined system can refrigerate the engine bleed air when recycling and utilizing the thermal energy of bleed air, which can not only improve the level of thermal energy, but also guarantee the modern aircraft’s excellent performance owning to decrease the use of ram air. As mentioned above, the power generation system by waste heat energy in bleed air is an effective way to solve the ‘thermal problem’. As working fluid is the essential factor to power generation system based on Ranking cycle, this paper discussed the choosing of optimum working fluid applied to this specific application technology in aircraft.

2. Calculation principles of Rankine cycle system.
As shown in Fig.1 (a) and (b), the working fluid at point 1 comes into evaporator to absorb the heat energy and begins to evaporate. Afterwards, it becomes superheated vapor with both high temperature and high pressure at point 2, and then the vapor comes into the turbine to expand to point 3. Next, it
enters condenser to release heat and begins to condense until it gets the state of point 4. In the end of a

cycle, it comes into the pump to increase fluid’s pressure to the evaporation pressure and arrives back
to point 1.

The expanding power in turbine:

\[ w_g = h_2 - h_3 \]  \hspace{1cm} (1)

The compressing power in pump:

\[ w_h = h_1 - h_4 \]  \hspace{1cm} (2)

The net power of cycle:

\[ w_{net} = w_g - w_h = (h_2 - h_3) - (h_1 - h_4) \]  \hspace{1cm} (3)

The heat absorption of system:

\[ q = h_2 - h_1 \]  \hspace{1cm} (4)

The thermal efficiency of cycle:

\[ \eta = \frac{w_{net}}{q} = \frac{(h_2 - h_3) - (h_1 - h_4)}{(h_2 - h_1)} \]  \hspace{1cm} (5)

Fig.1 System operation flowchart and the temperature-entropy diagram

3. Selection method of the optimum working fluid.

3.1. The preliminary selection.

As mentioned, the temperature of waste heat source is about 400 degree centigrade. We may just as

well select the working fluids whose critical temperature is larger than 150 degree centigrade from the

common fluids[2] attached to the Rankine cycle according to the rule that fluids with high critical

temperature usually have the better performance during Rankine cycle showed by several references

[3,4,5,6].
This paper selected 19 working fluids such as the following, toluene, n-butane, n-pentane, n-hexane, n-heptane, n-octane, n-nonane, n-dodecane, isopentane, cyclohexane, methanol, ethanol, R11, R113, R114, R123, R141b, and R365mfc, water. Among these fluids, water has the largest critical temperature which could reach 374 degree centigrade, and it also can satisfy the temperature requirement of the combined power generation system.

3.2. The method of calculation.
As mentioned, the temperature of the aircraft engine bleed air is nearly 400 degree centigrade under cruising condition. So we can pick the evaporation temperature of working fluids as 20 degree centigrade lower than their respective critical temperature. Considering that the heat sink of aircraft are cabin air and low temperature fuel oil, we may make the condensation temperature of working fluids be 50 degree centigrade. Furthermore, we could control the superheating temperature and the undercooling temperature to be 10 and 5 degree centigrade respectively. We must point out that it is necessary to observe the dryness of steam at point 3 and make it higher than 0.86[7] all the time to ensure the safe operation of turbine, even all the system.

On this foundation, we can acquire the optimum working fluid on the basis of the calculation principles of the Rankine cycle system mentioned above with the help of MATLAB for the proposed system attached to different calculation aims such as the most net power of cycle, the most heat absorption of system, and the highest thermal efficiency of cycle.

3.3. Calculation results based on the most net power.
As shown in Fig.2, we can see the trend on net power of different working fluids.

In cycle net work
According to Table.1, among 19 fluids, ethanol has the most net power to 291.04 KJ/Kg. And n-dodecane and toluene are following with 253.77 KJ/Kg and 219.38 KJ/Kg respectively. According to the engineering experience, when we pick ethanol as the working fluid of this combined power generation system and make the mass flow be 1000Kg/h, then the electricity output could approach up to 80.8KW if the loss of generator is ignored.
Table 1. The results of cycle network and output power

| Fluids      | Cycle net work / (KJ/Kg) | Output power by 1000kg/h mass flow / KW |
|-------------|--------------------------|----------------------------------------|
| toluene     | 219.38                   | 60.94                                  |
| n-butane    | 69.98                    | 19.44                                  |
| n-pentane   | 108.35                   | 30.10                                  |
| n-hexane    | 139.63                   | 38.79                                  |
| n-heptane   | 165.08                   | 45.86                                  |
| n-octane    | 188.20                   | 52.28                                  |
| n-nonane    | 207.74                   | 57.71                                  |
| n-dodecane  | 253.77                   | 70.49                                  |
| isopentane  | 95.43                    | 26.51                                  |
| cyclohexane | 183.33                   | 50.93                                  |
| methanol    | 146.03                   | 40.56                                  |
| ethanol     | 291.04                   | 80.84                                  |
| R11         | 48.38                    | 13.44                                  |
| R113        | 49.00                    | 13.61                                  |
| R114        | 23.05                    | 6.40                                   |
| R123        | 43.33                    | 12.04                                  |
| R141b       | 65.85                    | 18.29                                  |
| R365mfc     | 53.52                    | 14.87                                  |
| Water       | 102.00                   | 28.33                                  |

3.4. Calculation results based on the most heat absorption.
Under some certain conditions, it is significant to recycle most heat energy to the extreme extent to obtain the most temperature drop of bleed air. Then what we need is not the most power output but the most heat absorption in the evaporation process. As shown in Fig.3, we can see the trend on heat absorption of different working fluids.

![Fig.3. The comparison of calculation results](image)

In cycle heat absorption
According to Table 2, among 19 fluids, water has the most net power up to 1339.94 KJ/Kg. And ethanol and n-dodecane are following with 1102.11 KJ/Kg and 1085.96 KJ/Kg respectively.
### Table 2. The results of cycle heat absorption

| Fluids          | Cycle heat absorption (KJ/Kg) |
|-----------------|-------------------------------|
| toluene         | 757.18                        |
| n-butane        | 469.71                        |
| n-pentane       | 573.47                        |
| n-hexane        | 664.52                        |
| n-heptane       | 747.48                        |
| n-octane        | 827.12                        |
| n-nonane        | 899.22                        |
| n-dodecane      | 1085.96                       |
| isopentane      | 534.80                        |
| cyclohexane     | 726.26                        |
| methanol        | 974.39                        |
| ethanol         | 1102.11                       |
| R11             | 228.60                        |
| R113            | 234.39                        |
| R114            | 167.62                        |
| R123            | 229.97                        |
| R141b           | 306.26                        |
| R365mfc         | 303.95                        |
| Water           | 1339.94                       |

#### 3.5. Calculation results based on the highest thermal efficiency.

As shown in Fig. 4, we can see the trend on thermal efficiency of different working fluids.

![The comparison of cycle thermal efficiency by different fluids](image)

**Fig. 4.** The comparison of calculation results

In cycle thermal efficiency, according to Table 3, among 19 fluids, toluene has the highest thermal efficiency up to 28.97%. And ethanol and cyclohexane are following with 26.41% and 25.24% respectively.
Table 3. The results of cycle thermal efficiency

| Fluids            | Cycle thermal efficiency /% |
|-------------------|----------------------------|
| toluene           | 28.97                      |
| n-butane          | 14.90                      |
| n-pentane         | 18.89                      |
| n-hexane          | 21.01                      |
| n-heptane         | 22.08                      |
| n-octane          | 22.75                      |
| n-nonane          | 23.10                      |
| n-dodecane        | 23.36                      |
| isopentane        | 25.24                      |
| cyclohexane       | 25.24                      |
| methanol          | 14.99                      |
| ethanol           | 26.41                      |
| R11               | 21.16                      |
| R113              | 20.90                      |
| R114              | 13.75                      |
| R123              | 18.84                      |
| R141b             | 21.50                      |
| R365mfc           | 17.61                      |
| Water             | 7.61                       |

3.6. Thermodynamic performance analysis of moist working fluids.
We can distinguish easily from Fig.4 that as the typical moist fluid, water has the lowest thermal efficiency as low as 7.61%. However, we can see that the net power of water is not the minimum value from Fig.2. The main cause is that when we use water as the system working fluid, we must control the condensation pressure to ensure that the dryness of steam at point 3 is larger than 0.86 and thus to ensure the safe operation of turbine. Compared with dry working fluids, the higher condensation pressure will decrease the net power and the thermal efficiency. Furthermore, methanol is also a moist fluid under this temperature range, according to the calculation, we can see that the condensation temperature must be 130 degree centigrade at least to guarantee the value of the dryness of steam at point 3 as mentioned above.

4. Summary
1) Combining Ranking cycle with aircraft environment control system can not only refrigerate the engine bleed air to make it meet the system operation criteria, but also decrease the utilization of ram-air and ensure the performance of modern aircraft. Furthermore, this method can generate power by using waste heat energy, transfer thermal energy to electronic energy and upgrade the level of energy.

2) Combining Ranking cycle with aircraft environment control system can not only refrigerate the Targeting at the largest cycle net power, calculation result showed that ethanol performed best upon 19 working fluids, and the acquired recycling net power of unit mass ethanol was 291.04KJ/Kg. n-dodecaneal and toluene took the following position, were 253.77KJ/Kg and 219.38KJ/Kg respectively. The cycle net power of R114 was the least, and the acquired net power of R114 is just 23.05KJ/Kg.

3) Combining Ranking cycle with aircraft environment control system can not only refrigerate the Targeting at the highest cycle thermal efficiency, calculation result showed that water performed best upon nineteen working fluids, and the maximum value was 28.97%. Ethanol and cyclohexane
were following with 26.41% and 25.24% respectively. The value of cycle thermal efficiency by water was the least with just 7.61%.

5) Combining Ranking cycle with aircraft environment control system can not only refrigerate the As far as moist working fluids, controlling condensation pressure to ensure that the dryness of steam at point 3 in Fig.1 is larger than 86% is needed to secure the system’s safety. But it is necessary to point out that this method will weaken the cycle net power and thermal efficiency.

6) Combining Ranking cycle with aircraft environment control system can not only refrigerate the what we must point out is that the selection methods must consider the realistic application situation. And even if ethanol, toluene, n-dodecane and cyclohexane have the satisfied thermodynamic properties, there are also so many restrictive conditions due to their unstable chemistry properties.

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