Abstract

Renewable aided power generation (RAPG) is capable of integrating low to medium temperature renewable resources in the case of 90-260°C into a conventional Rankine cycle power plant to replace the extraction steam of power plant. In a RAPG plant, renewable fluid is used to preheat the feed water of power plant, instead of the extraction steam, thus the replaced extraction steam expand further in steam turbine to generate electricity. The renewable fluid can be used to replace the extraction steam of power plant at different extraction points and replace different percentage of extraction steam. In the current study, a model of RAPG plant has been developed in order to calculate the technical and economic assessment of RAPG plant for different operational conditions. The overall efficiency of the RAPG plant and the renewable thermal share of power generation with different replacement of extraction steam at different operational load have been studied in this paper. A 1000 MW ultra supercritical power plant has been used as case study, the power plant at 100%, 75%, 50% load have been studied in this paper.

Introduction

In many parts of the world, with the concerns about the security of energy supplies and the environment problems caused by fossil-fired power plants, renewable energy has been attracting more and more attention. The report from the U.S. Energy Information Administration shows that renewable energy sources are the fastest growing sources of electricity generation, at 2.8 percent per year from 2010 to 2040. Although, renewable (geothermal and solar) alone powers plant offers the advantages of low greenhouse gas emissions, the efficiency and cost of these power plants of low to medium temperature are not so attractive [1]. As coal which generated 40 percent of world electricity in 2008, integrated the renewable energy into existing coal fired Rankine cycle power plant is a possible method to use low to
medium temperature renewable resources [1]. It shows that integrated the renewable energy into existing Rankine cycle power plant can significantly increase the efficiencies than the stand alone renewable energy power plants [2]. Kolb pointed that integrated renewable energy into existing Rankine cycle power plants offer economic advantages of lower infrastructure cost than renewable alone power plants [3].

Integrated into renewable energy into coal fired power plant is so-called RAPG. To author’s knowledge, two kinds of renewable energy (geothermal energy and solar energy) have been analysed by the previous studies. Hou et al. in a recent paper analyzed the SAPG plant under different operational modes (power boosting and fuel saving) and part load conditions. In the paper of Hou, the higher pressure feedwater heaters have been replaced by solar energy as case study. The results indicated that the lower-load of coal-fired unit that solar aid, the lower solar to electric efficiency will be and the technical performance of RAPG plant is depended on the solar radiation intensity and the electric load demand [4].

In practice, the power plant would not operate on the design condition in most of time. Due to the changes of electricity demand, the power plant often operates under part load conditions. Hou et al. analyse the performance of solar preheating system under various load (100%, 75% and 50%) conditions. A 300MW coal fired plant is used as case study and the high pressure feedwater heater is replaced for analyse the performance of solar preheating system. In this paper, a 1000MW ultra-supercritical power plant is used as case study, the renewable with different temperature to replace different level of feedwater heaters have been analysed.

**Renewable Aided Power Generation**

Most of the coal fired power plants are based on the regenerative Rankine cycle, in which parts of the steam (extraction steam) is extracted from the turbine to preheat the feedwater (FW) to boiler. The result is the improvement of the thermal efficiency of power plants, however, the power production per unit steam is reduced. In Renewable aided power generation (RAPG), the renewable energy is used to replace the extraction steam to partially or fully preheat the FW to the boiler. The extraction steam is replaced by solar heat, so that the saved steam can then expand further in the lower stages of the turbine to produce electricity. Figure 1 shows the concept of SAPG system. As shown in Fig. 1, solar energy is integrated through a by-pass heat exchanger which is named renewable preheater in Fig. 1. The FW flows entering the renewable preheater is controlled by the valve. The key difference between the RAPG and other multi-sources hybrid (boosting) power generation is that the renewable energy (heat) does not enter the turbine directly. The benefit from RAPG technology can come from two operational modes: power boosting mode which the boiler consumes the same amount of fuel and the mass flow rate of FW entering the boiler is kept constant and fuel saving mode which the power output of the steam turbine remains constant [3].

![Fig. 1 Schematic diagram of FWH with a renewable fluid by-pass heat exchanger](image-url)
Modeling Description

Integrating the renewable fluid into a regenerative Rankine cycle affects not only the feedwater flows but also the steam mass flows through the various stages of the turbine and the boiler. The performance parameters of the Rankine cycle power plant would change, and the technical performance of power plant should be re-analyzed. Thus, the technical performance of each parts of power plant should be recalculated. The mathematical modeling of RAPG plant consists of modules for simulating the steam turbine stages, the feedwater heaters, the deaerator the condenser and the boiler. In addition, a special evaluation module is developed to estimate the benefits and performance of the RAPG. The model is based on engineering thermodynamic principles.

When the renewable fluid is used to replace the extraction steam of power plant, the steam mass flows through the various stages of the turbine would change. The changes to the mass flow rate through the steam turbine result in the steam turbine being operated on off-design condition. An off-design condition in turn leads to a change in the exit pressure of the turbine and so to the inlet conditions of the subsequent turbine stages. Stodola’s Law, which is attributed to Aruel Stodola, provides a method to calculate these changes. According to this law (also called the Ellipse law) the exit pressure for a multistage turbine changes with the mass flow rate through the turbine. Stodola’s law can be written as [5]:

\[ \frac{D_1}{D_{10}} = \frac{p_1 - p_2}{p_{10} - p_{20}} \times \left( \frac{T_{10}}{T_1} \right) \]

where the \( D_1 \) is design flow rate, the \( D_{10} \) is off-design flow rate, \( p_1 \) is the designed inlet pressure, \( p_2 \) is the designed outlet pressure; \( p_{10} \) is the inlet pressure under off design condition, \( p_{20} \) is the outlet pressure under off-design conditions, while \( T_1 \) and \( T_{10} \) is the inlet temperature under the design condition and the off-design condition, respectively.

Case study and discussion

In order to validate the mathematical model of RAPG plant, the heat balance diagram of a 1000MW ultra supercritical power plant is used as case study. Figure 2 shows the heat balance diagram of 1000MW ultra supercritical Rankine cycle power plant at design load. As shown in Fig. 2, the 1000MW ultra supercritical Rankine cycle power plant has 7 closed feedwater heaters and 1 deaerator. The extraction points A and B are from the HP steam turbine, the extraction points C, D and E are from the IP steam turbine and the extraction points F, G and H are from the LP steam turbine.

Table 1 shows the replacement scenarios of this study. The ultra supercritical power plant at 100%, 75% and 50% are studied. The renewable resources with temperature of 300°C and 160 °C are used as case study to replace the HP feedwater heaters and LP feedwater heaters separately.

Renewable thermal share of power generation is the ratio of output from renewable to the output of power plant. In the power boosting mode, the renewable power production is the extra power output of steam turbine. In the fuel saving mode, the renewable power production is the the difference between the plant power output at the reduced boiler flow rate without any no renewable input, and the designed plant output. Figure 3 shows the power output of renewable energy of different replacement scenarios for different operational load of power plant. The result shows that replacement of higher pressure FWH could produce more work than lower pressure FWH. Fig.3 shows that replacement of high pressure FWH can produce about 3-4 times of electricity output than replacement of low pressure FWH. The result of Fig. 4 also shows that when the power plant works at 75% or 50% operational load, the power output from renewable energy is not 75% or 50% of 100% operational load. It is shown that when the high pressure FWH is replaced by renewable energy at 100% operational load of power plant (scenario 1), the power output of RAPG is 181.1 MW for power boosting and 191 MW for fuel saving. At scenario 3, the
power output of RAPG is 116.6 MW for power boosting and 133.6 for fuel saving. The output of scenario 3 is about 64.3% for power boosting and 68.5% for fuel saving of scenario 1.

Figure 4 shows the renewable thermal share of power production of scenario 1, 3, and 5. Figure 5 shows the renewable thermal share of power production of scenario 2, 4, and 6. It is shown that when the high pressure FWH is replaced by renewable energy, the renewable thermal share of power production vary from 85% to 90%, while when the lower pressure FWH is replaced by renewable energy, the renewable thermal share of power production vary from 95% to 98%. The result also shows that the RAPG plant works on 50% operational load have the lowest renewable thermal share of power

Fig. 2 Schematic diagram of heat and mass balance of 1000MW ultra supercritical power plant.

Fig. 3 Power output of renewable energy of different replacement scenarios for 100%, 75% and 50% operational load.

Fig. 4 Power output of renewable energy of different replacement scenarios for 100%, 75% and 50% operational load.
production while the RAPG plant works on 100% operational load have the highest renewable thermal share of power production.

| Operational load | Temperature of renewable resources | Replacement scenarios | Scenario number |
|------------------|------------------------------------|------------------------|----------------|
| 100%             | 300°C                              | Replacing extraction steam A-C | 1              |
|                  | 160°C                              | Replacing extraction steam E-H | 2              |
| 75%              | 300°C                              | Replacing extraction steam A-C | 3              |
|                  | 160°C                              | Replacing extraction steam E-H | 4              |
| 50%              | 300°C                              | Replacing extraction steam A-C | 5              |
|                  | 160°C                              | Replacing extraction steam E-H | 6              |

**Conclusion**

The behaviour of the RAPG plant under different operational conditions (power boosting and fuel saving) for different load of power plant have been studies. The results shows that, replacement of high pressure FHW produce more electricity than replacement of low pressure FWH. The results of power output from renewable energy of different load power plant shows that renewable energy used to replace full load power plant produce more electricity than 75% load and 50% load, however, the output of electricity from renewable is not in direct proportion to the load of output of power plant. When the high pressure FWH is replaced by renewable energy, the renewable thermal share of power production is higher than replacement of low FWH. And it is shown that RAPG works on 50% load have the lower
renewable thermal share than 75% load and 100% load have the highest renewable thermal share of power production.

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Biography

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