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Review of the Method of Marnoch Heat Engine Recovering Heat from Coal-Fired Power Plants

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ABSTRACT: Heat released from the stacks of coal-fired power plants is a resource that can be harnessed. This paper examines the performance of MHE in recovering useless heat from the main stack in a coal-fired power plant. The MHE units that are installed in the stack have eight (four pairs) shell and tube heat exchangers. The heat recovered by MHE is transferred to electricity and used in the coal-fired power plant. The results show that MHE is utterly useful in recovering heat from coal-fired power plant. The MHE units improve the efficiency of the power plant and decrease the amount of CO_2 emission, which is beneficial for environmental protection.

1. INTRODUCTION

In the most of conventional coal-fired power plants, which are only invented for electricity generation, 2/3 of fuel energy is wasted through stack gases and cooling water of condensers and so on, only 1/3 of fuel energy is useful. There are many different chemical elements in exhaust gas that is emitted from the coal-fired power plant. They are sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs), and various trace metals like mercury [1]. With the effort of government in many countries, the amount of SO_2, NOx and PMtotal saw a sharp decrease from the 1990 to 2018[2]. However, CO_2 is the notable element in the exhaust gas. Carbon dioxide (CO_2), which is an important greenhouse gas, can be emitted from the coal-fired plants.

There is a heat engine called the Stirling engine that can recover gas to produce electricity, but it causes a huge loss if connected with lower temperature heat sources [3].

This paper mainly shows the possibility of recovering exhaust gas from coal-fired power plants by MHE through literature research. This is a new way of using useless power that can be beneficial to the environment and improve the efficiency of heat energy, which provides a reference for environmental protection and improvemen.

2. STIRLING ENGINE

Robert Stirling invented the Stirling engine in 1816. After that, people improved this engine many times, so there are already many types of Stirling engines (e.g., Alpha, Beta and Gamma type Stirling engines). They all follow the Stirling cycle. Figure 1shows the P-V and T-S diagrams of Stirling cycle by (a) and (b) respectively. There are 4 steps in the Stirling engine: In process1-2, isothermal expansion occurs when heat is absorbed from the heat source, which will cause an increase in pressure and push the piston upward. In process2-3, isovolumetric heat removal to a heat sink occurs. The piston pushes the gas into heat sink. In process3-4, isothermal compression occurs. The gas that is pushed into the heat sink will be compressed. Heat is removed by the heat sink. In process4-1, isovolumetric heating occurs. Cooled gas enters the portion that is heated by the heat source [4].

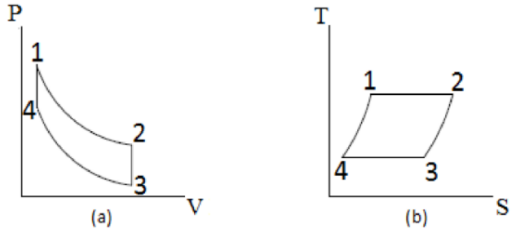

Figure 1 (a) P-V diagram and (b) T-S diagram of Stirling engine [4]

3. MARNOCH HEAT ENGINE

3.1. Marnoch cycle

The Marnoch cycle is quite familiar with the Stirling cycle, but there is a huge difference between these two cycles. That is: after each stroke, the area of the P-V diagram for the Marnoch cycle reduces, instead of being stable like the area of the P-V diagram for Stirling cycle. That is because the compression pressure increases and expansion pressure decreases after every stroke [6]. The P-V diagram can be seen in Figure 2.

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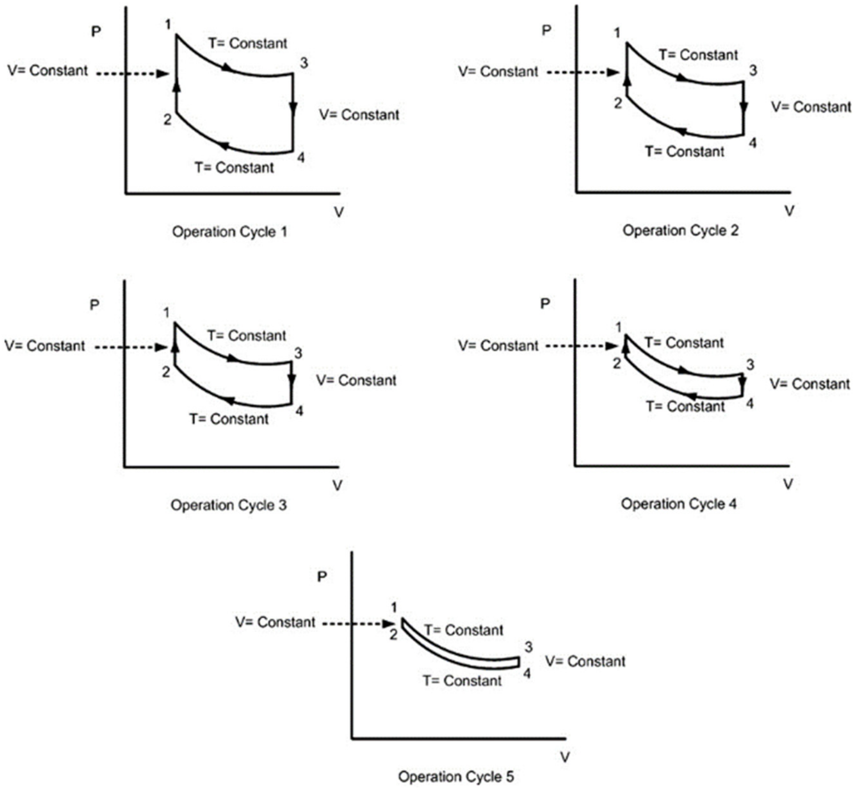

Figure 2 Five operation cycles of the MHE [5]

Also, there are two differences between these two heat engines. They are: 1) In the MHE, all the energy that is released from the piston is able to be transferred to an electric generator, different from the Stirling engine, the compression process also needs some mechanical work that is resealed from flywhell. 2) In the MHE, the piston can be placed apart from the heat exchanger, which makes MHE able to create pressure differences from temperature differences by using a variety of sources [6]. All the differences cause the MHE that has some advantages when compared with a Stirling cycle.

3.2. The structure of MHE

This section is going to describe the structure of MHE. It can be seen from Figure 3 that the components of MHE. There are two main parts of the MHE: the heat engine system and the transmission system. Detailed components can be seen in Figure 4.

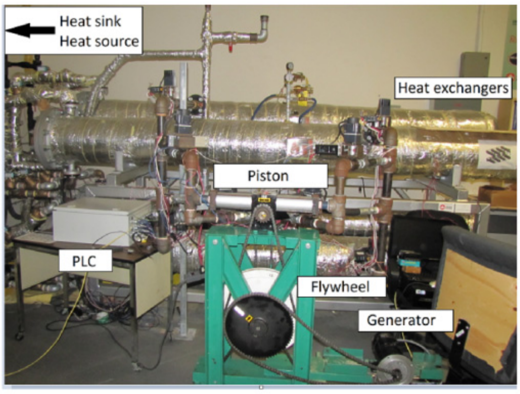

Figure 3 Photograph of the MHE [4]

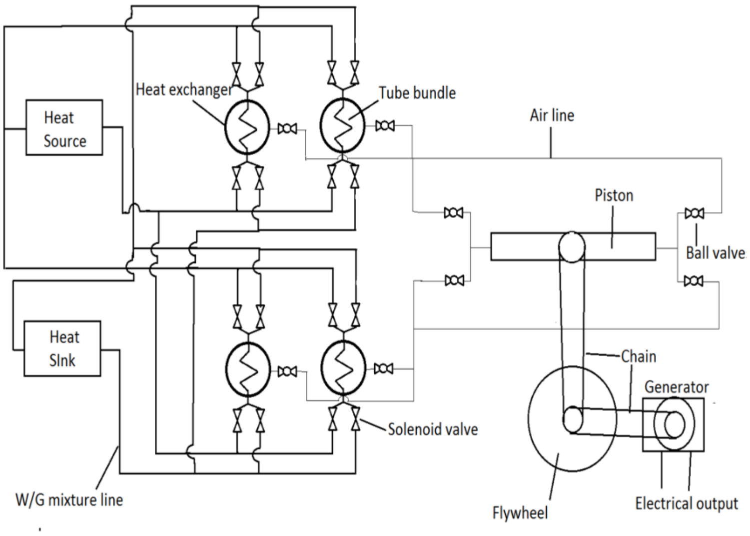

Figure 4 Schematic of the MHE [4]

3.3. The working principle of MHE

For the heat engine system shown in Figure 4, there are two heat exchangers that contain tube bundles that are connected to the heat source and heat sink. Several solenoid valves manage the flow of water glycol(W/G) mixture into the tube bundle from a heat source or heat sink. The working fluid is pressurized dry air, which fills in the heat exchangers, and is able to activate a pneumatic piston.

As for the transmission system in Figure 4, it is connected to each heat exchanger by ball valves, which are controlled by electric motors. These four ball valves control the direction of the motion of piston, so the piston can perform reciprocating motion.

The flywhell receives the energy from the piston by a chain and finally it reaches the generator in the same way.

All of the motion of valves in the whole system are controlled by a PLC, a common computer for automation of machinery. As a result, in most cases, human input is unnecessary [4].

In short, the process of MHE can be divided into two big steps: 1) transfer heat energy into mechanical energy by piston assembly. 2)transfer mechanical energy into electric energy by generator.

4. ANALYSIS OF COAL-FIRED POWER PLANT

Coal-fired power generation is a common way for many countries to create electricity. It uses heat energy that is produced during burning coal to heat water and convert water into high temperature and pressure water vapor. Water vapor pushes the electric generator to create electricity.

Coal-fired power is a quite popular way for generate electricity in the world. The production of coal-fired power plants is expected to increase by 44% in 2030, and 40% of the actual production of electricity in the world is from coal-fired power generation. [7]

The most common way to dispose of exhaust gas from coal-fired power plants is to release it into the environment. For environmental protection and improvement of efficiency, people always try to recover heat from heat sources. For coal-fired power plant, there are many potential sources to collect heat. From the analysis of Yatagan thermal power plants, Hasan Huseyin Erdem et al. [8], there are two better heat sources in the coal-fired power plants: 1) The cross pipe between low pressure and intermediate pressure turbines. 2) Stack gas is also a good choice. This paper mainly talks about the second possibility of extracting heat.

5. ANALYSIS OF MHE IN THE COAL-FIRED POWER PLANT

5.1. System description

For the second point of extracting heat, stainless steel coils of hot heat exchangers lie in the main stack, which are mainly for recovering and transferring heat to the liquid in the MHE. There are four pairs of shell and tube heat exchangers in one MHE. Heat is gathered in the heat reservoir and transferred by glycol water mixture to the working fluids, which is the soul of the work of MHE. Therefore, the pressure of the gas, which is in the shell increases. In contrast, the gas pressure in the rest of heat exchangers decreases since the liquid cools the gas. Low-pressure and high-pressure shells are connected when the figure for pressure differential is highest, and then gas is able to move from the high shell to the low shell until the pressure inside the shell equalizes [8]. This paper mainly talks about an MHE unit instilled in the main stack that has eight (four pairs) of shell and tube heat exchangers (Figure 5).

The temperature of the gas in the main stack is around 349k to 370k, as searched by ChuYuan Peng in a power plant in Su Zhou [9]. For the chemical elements in the exhaust gas, after desulfurization and other treatments, CO_2 has the highest content in the gas, so there is no risk of corrosion.

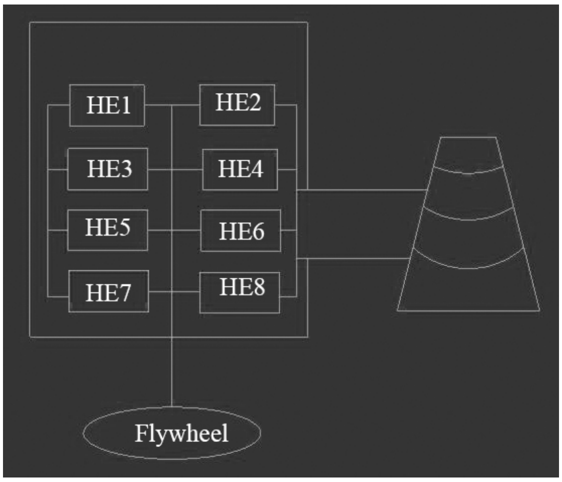

Figure 5 Schematic of heat recovery system from main stack

5.2. Analysis for the main stack

There are two equations deduced by P. Saneipoor et al.

$$\dot{m}_{A/F}h_{SI} + \dot{m}_{WGin}h_{WGin} = \dot{m}_{SO}h_{SO} + \dot{m}_{WGout}h_{WGout} + \dot{Q}_{loss} \quad (1)$$

Equation (1) shows when there is a steady state operation in the heat exchanger inside the stack, the amount of heat gained from the main stack. Where $\dot{m}$ is the mass flow rate[kg/s] and h is specific enthalpy[J/kg]. A/F is air/fuel ratio, SI and SO is stack inlet and outlet respectively. WG is a water glycol mixture. This equation shows the balance of mass for air/fuel entering the system and out of the main stack, and the balance of mass for WG entering the heat exchanger and out of the main stack. There is some energy loss when the heat is transferred from the gas to the system.

$$\dot{m}_{A/F}ex_{SI} + \dot{m}_{WGin}ex_{WGin} = \dot{m}_{SO}ex_{SO} + \dot{m}_{WGout}ex_{WGout} + \dot{E}x_{loss} + \dot{E}x_{dest} \quad (2)$$

where ex is specific exergy[J/kg]. $\dot{E}x_{dest}$ is the energy destroyed because of friction losses or transferred energy through tube bundles. Equation (2) shows the exergy equation for main stack under environmental temperature and pressure is 288 k and 103.4 kPa respectively. In exergy analysis, this condition corresponds to the dead state [5].

5.3. Exergy analysis

Exergy is able to measure the energy availability [10]. In order to determine the performance of the MHE system in different environmental situations, exergy analysis is essential, and it is a really helpful tool to design and improve the whole MHE system [11].

$$\dot{E}x_i = \dot{m}[(h_i - h_0) - T_0(s_i - s_0)] \quad (3)$$

where h_i, s_i are specific enthalpy and entropy in the system. Similarly, h_0, T_0, s_0 are specific enthalpy, temperature and entropy in the environment respectively. Equation (3) is deduced by P. Saneipoor et al. $\dot{E}x_i$ is the physical exergy of each point. Through this equation, the availability of this recovery system can be determined by measuring some parameters near the main stack, which is useful for the improvement of the system [5].

5.4. Analysis of heat exchanger

There are three modes of the heat exchanger:

(1) This mode starts when the hot heat exchanger accumulates more air than the cool heat exchanger. In this mode, the heat exchanger that contains more air is heated, while the heat exchanger that contains less air is cooled. Therefore, the pressure differential in this mode is higher than in the initial period.

(2) In the second mode, cold and hot liquid are delivered to the heat exchangers in order to keep the almost isothermal expansions and compressions. Due to the number of heat delivered to the heat exchangers and the same figure removed from the heat exchanger are unchanged, the process is not isothermal. The temperature of heat sink and heat source are constant, and the liquid flow rate in heat exchangers is constant. However, the air mass flow from/ into the shell is always changing.

(3) The third mode begins when the pressure of pressurized air in the hot and cold heat exchangers is same. In this period, all the valves are closed and there is no fluid entering is removed from the heat exchangers [8].

$$\int_0^t \left(\frac{m_{Air,out}}{dt}\right) dt = m_{initial} - m_{final} \quad (4)$$

where $m_{Air,out}$ is the air mass flow rate that is leaving the hot heat exchanger. $m_{initial}$ is the initial air mass in one shell. Similarly, m_{final} is the final air mass in one shell. Therefore, the perfprmance of the gas inside the heat exchanger can be calculated by the equation (4) [5].

5.5. System efficiency

It is important to find the efficiency of the system, so this section talks about the equations for the MHE system efficiency.

The overall efficiency of MHE system is:

$$\eta = \frac{\dot{W}_e}{\dot{Q}_{in}} \quad (5)$$

$\dot{W}$ is the work rate[W] and $\dot{Q}$ is heat flow rate[W]. Equation (5) means the whole efficiency of the system is the electricity output divided by thermal energy input. $\dot{Q}_{in}$ is calculated by $\dot{m}_{WGin}h_{WGin}$.

Similarly, the exergy efficiency of the MHE system is:

$$\eta_{EX} = \frac{\dot{W}_e}{\dot{Ex}_{in}} \quad (6)$$

$\dot{E}x$ is the exergy flow rate[W].

$$\dot{Ex}_{in} = (1 - \frac{T_0}{T})\dot{Q}_{in} \quad (7)$$

These equations all deduced by P. Saneipoor et al. [5]

6. RESULT

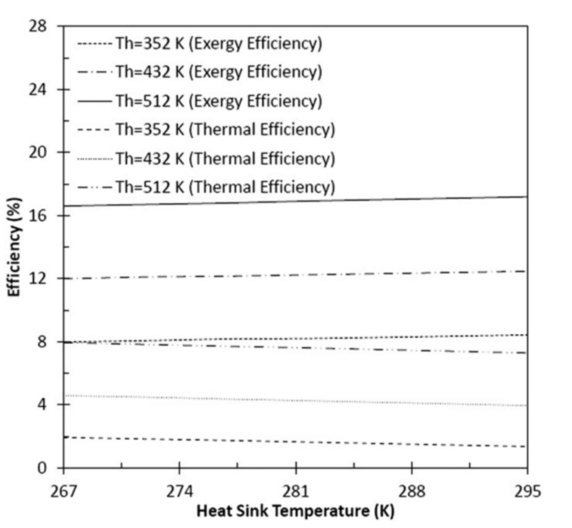

Figure 6 Thermal and exergy efficiencies of MHE under different heat sink temeprature [8]

It can be clearly seen from Figure 6 that the relationship between the heat sink temperature and the thermal/exergy efficiency under different temperatures of the heat source. As the temperature of the gas at main stack is around 360K, the thermal efficiency is about 2%, and there is a slight drop with the ambient temperature increases. The exergy efficiency is around 8%, in contrast to the decrease, there is a slight increase among due to the increasing of ambient temperature. In short, the efficiency of recovering the exhaust gas from the main stack in a coal-fired power plant is not so high, but there is no doubt that it can work and there is only a small limitation to the environmental issues.

7. CONCLUSION

This paper explores the possibility of MHE that recovers heat from coal-fired power plants. It is possible to recover heat energy from coal-fired power plant by MHE, the thermal efficiency and exergy efficiency are 2% and 8% respectively and these two efficiencies rise when the temperature of heat source goes up. MHE can reuse the exhaust gas at a low temperature, which is quite suitable for coal-fired power plants.

Because of the limitation of the ability of author, there is no data about the output of electricity, so further experiments can measure the relevant data.

From the introduction page of the MHE, it can be obtained that this technology is currently being marketed for use by companies that emit waste into the environment. In the future, it may be used in residential areas, such as the gas from rural cooking and smoke emitted by the car or trunk. This also needs to be researched.

To a large, MHE has huge potential to recover heat energy, and it is possible for it to have huge scale of application. Although more experiments and research need to be done, it is still a good heat engine for reusing energy.

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