System design and analysis on organic Rankin cycle for asphalt plant’s waste heat recovery

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Abstract. An organic Rankin cycle system was investigated with the purpose of utilizing the waste heat from the asphalt plant’s rotary dryer. The factors that have the impact on the heat source properties by means of combustion and heat transfer were discussed. The ORC system was developed utilizing R245fa as the working fluid, in consideration of the operation conditions of the cycle and its environmentally-friendly characteristics. An evaporator which support phase-change heat transfer was chosen, because most of the energy is in latent heat of the vapour. A radial inflow turbine was selected due to the output power of the system. The operation data of the asphalt plant was taken to evaluate its potential of energy recovery. It can generate 104.4kW electricity when the ORC system is combined with JD3000 asphalt plant. If the electricity is used to the plant itself, 17.1% of electricity power could be saved. The scheme proposed could provide a new solution to the waste heat recovery of the asphalt plant.

1. Introduction

Connectivity of infrastructure construction is the core component of the “Silk Road Economic Belt and the 21st-Century Maritime Silk Road”. And roadway construction plays an important role of connectivity. At present, the pavement of these motor roads and airfields is made of hot mix asphalt (HMA), a mixture prepared in asphalt mixing plants. In these HMA production plants, the aggregates are conveyed from stockpiles to dryers, where they are heated to a temperature between 150 and 200 ℃. The bitumen is heated to a certain temperature in order to coat the aggregates. Then the aggregates are mixed with the bitumen, producing the final HMA mixture[1].

Asphalt mixing plants consumes a large amount of energy in the transportation industry. A conservative figure of how much energy is needed to manufacture one metric ton of HMA is around 85 kWh[2]. Meanwhile the emission is also relatively large, which not only leads to the waste of resources but also causes harm to the environment. Therefore, energy saving and emission reduction of asphalt mixing plants should be highly paid attention to[3].

Relevant research has been conducted by engineers and scholars in various countries with regard to saving the energy and reducing the emission[4,5]. Since the heating process is the critical part, methods are almost related to it. The most common ways are reducing the temperature of the hot mix requirements, improving the performance of aggregate dry heating system, and strengthening the management of stock pile[2,6]. Warm mix asphalt (WMA) technology which can reduce the mixing temperature is a promising way in asphalt paving industry[7]. Wang et al summarized the best practices and recent research findings on warm mix rubberized asphalt concrete, then analysed its strengths and drawbacks[8]. Peinado et al presented the energy and exergy analyses of the heating process, and proposed some guidelines to achieve this goal, such as eliminating the moisture content in the process.
aggregates, decreasing the exhaust temperature\textsuperscript{[2]}. There are many researchers focusing on the structural parameter optimization to enhance the heat transfer efficiency between the high temperature gases and the aggregates\textsuperscript{[9,10]}. The common approaches are using appropriate blades and adjusting the material curtain density.

Based on reviewing the studies conducted to saving the energy in the asphalt mixture production process, it may be concluded that very few studies are related to the waste heat recovery of the gas from the dryer, though it still has lots of energy. As a matter of fact, the waste heat recovery of the fuel gas has become a hot topic in recent years\textsuperscript{[11]}. But the researches are in the fields of metallurgy, cement production, boiler, engine, and so on\textsuperscript{[12-14]}. No one focus on the waste gas utilization of the asphalt mixture plants. This was the motivation by performing the present study. Organic Rankine cycle(ORC) is one of the promising low grade thermal energy recovery technologies. The ORC units utilise the otherwise wasted energies and convert them into useful power. It is similar to the steam Rankine cycle, however, it utilizes organic compounds such as hydrocarbons and/or refrigerants that boil at low temperature and pressure compared to the water. It has been used to all kinds of low-temperature heat sources including geothermal energy, solar energy, waste heat energy and biomass energy\textsuperscript{[15]}. Due to the favourable characteristics of simple structure, high reliability, low cost and easy maintenance, it could be a solution to the waste heat recovery by supplying the asphalt mixture plants with the electricity.

In the present study, an ORC system which use the waste gas from the rotary dryer as the heat source was proposed. The thermodynamic performance of the system was analysed. This approach to utilize the waste gas in the asphalt mixture plants could give researchers and engineers a new solution to enhance the energy efficiency in the asphalt industry.

2. System configuration

2.1. Heat source property
Hot Mix Asphalt is made up of aggregates(sand and coarse aggregates), the filler and bitumen. Sometimes adhesion agents, modifiers or fibres are added to improve the performance of the product. Among the components, the graded aggregates constitute approximately 90% in mass of the mixture, while the bitumen is about 5%.

The HMA is manufactured in asphalt plants, where rotary dryer takes up the main energy consumption. It plays an important role in removing the moisture and heating the aggregates to a proper temperature. First the aggregates are transferred from the stockpiles to dryer, meanwhile the fuel and air are introduced into the combustor, then the aggregates are lifted and thrown by the helical blades installed inside the dryer. When the aggregates are dried and heated by the dryer, part of the dust is mixed with the fuel gases. In the end the exhaust gases are introduced into the dust collector. Since the gases contain dust, it is harder to use the exhaust heat.

There are many fuels that could be used in the combustor, such as heavy oil, diesel, natural gas, or micronized coal. The fuel can not only affect the exhaust gases, but also affect economical efficiency. In this work the liquid heavy oil is selected as the fuel.

The reaction between the heavy oil and air at a stoichiometric ratio $\lambda$, can be written as\textsuperscript{[2]}:

\[
C_{n_c}H_{n_H}S_{n_s}O_{n_O} (H_2O)_{n_H_{o,d}} + \lambda \left(n_c + \frac{n_H}{4} + n_s + n_O - \frac{n_O}{2}\right) (O_2 + 3.76N_2) \\
\rightarrow n_cCO_2 + \left(n_{H_{o,d}} + \frac{n_H}{2}\right)H_2O + n_sSO_2 + n_O NO_2 + \left(\lambda - 1\right) \left(n_c + \frac{n_H}{4} + n_s + n_O - \frac{n_O}{2}\right) O_2 \\
+ 3.76\lambda \left(n_c + \frac{n_H}{4} + n_s + n_O - \frac{n_O}{2}\right) N_2
\]

(1)

There are some gases generated from the combustion besides the water vapour. When the heat is transferred to the aggregates, the exhaust gas temperature decreases to about 120°C. With the purpose
of burning sufficiently, the import air is excessive. So the exhaust gas contains not only the products but also the nonreactive air and some dust involved from the heating process.

To use the waste heat of the gas, it is necessary to investigate its properties well. For example the components, thermal parameters and influence factors. Figure 1 illustrates the influences on the gas properties. The type of fuel, the flow rate and the inlet air fuel ratio have great impact on the combustion, which determine the gas components and the water vapour content. The rotary dryer’s structure and operating parameters such as length, tilt angle, blades configuration, and the rotate speed affect the aggregates curtain properties. Also the size distribution of aggregates and moisture content are other important factors. They affect the water vapour content and dust content of the gas. It is better to make the fuel combust sufficiently and let the heat transfer to the aggregates as much as possible. To achieve that goal the optimized rotary dryer design as well as a proper combustor is needed. Meanwhile, the longer aggregates contact with the hot gas in the dryer, the better the heat is used. The aggregates’ moisture is a very important parameter to control the performance of an asphalt plant. When a higher water content is present in the solids, the excess energy is needed, and the exhaust gases contain more water vapour.

2.2. ORC system configuration

Based on the heat source properties, the ORC system design scheme was proposed. Figure 2 shows the schematic of the ORC system.
result in blocking the bag. After filtering the dust, the waste gases flow into the evaporator to heat the medium. The ORC system operates as follows:

- **4-1**: The organic fluid evaporates in the evaporator absorbing the waste heat from the hot gases.
- **1-2**: The high pressure organic fluid is transported to the expander in which its thermal energy is converted to mechanical energy of shaft. The generator contact to the shaft and electricity is generated. The fluid expands to low pressure and flow to the condenser.
- **2-3**: The vapour is condensed to liquid in the condenser using the cooling medium.
- **3-4**: The low pressure fluid is transported to the liquid trap to store and then pressurized with a pump. After that another new cycle begins.

The electricity generated can be used by the asphalt plant which could save the energy cost by the electric equipments.

The liquid trap works as a buffer when there is disturbance in the hot gases. Since the hot source might have a fluctuation in the process of operation, adding the liquid trap can not only store the medium but also generate the electricity stable.

The corresponding temperature-entropy diagram of the simple organic Rankine cycle is shown in Figure 3.

![Temperature-entropy diagram of the simple ORC](image)

Figure 3. Temperature-entropy diagram of the simple ORC

If the exit temperature $T_2$ is high, the system can add a recuperator between the expander exit and the condenser. It can use residual heat after the expander for pre-heating the working fluid before it enters the evaporator.

The choice of working fluid is a very important aspect in the ORC system. Thermo-physical properties of working fluids have great impacts on the system efficiency, economic viability, components’ size, system stability, expander’s performance, safety and environmental issues. The selection of the working fluid is critical to achieve high cycle thermal efficiencies. It is better to get a good efficiency by using the medium with the critical temperature close to the maximum temperature of the heat source\(^{[15,16]}\). The temperature of the gas is about 120°C. R245fa is a great option not only because its critical temperature meet that requirement, but also has other advantages. It is safe, economical, and environment-friendly. Therefore, R245fa is selected in this system.

Evaporator is the key components in the system. There are some special characteristics which impact its configuration. The first one is the dust in the gases. Though it is filtered by the bag dust collector, it may contain some residual dust. The evaporator also needs a dust collection part too. Another one is the phase change problem. Due to that, the exit water should be treated particularly. This means the evaporator is different from the ordinary ones.

The expander is the core of the system and plays a critical role in determining the cycle efficiency\(^{[17,18]}\). The choice of the expander strongly depends on the cycle operating conditions, type of
working fluid and the range of net power output. According to the heat source properties, asphalt plant production rate and the conditions mentioned above, radial inflow turbine is selected.

3. Analysis methodology

3.1. Model description

Since the pressure on the heat source side of the evaporator is atmospheric pressure, there is no phase change of the exhaust gases except for the water vapour during the heat exchange process. It is convenient and reasonable to take those products and air as one substance to calculate the energy. If the specific heat is \( c_p \), the gas temperature drop from \( T_{e, in} \) to \( T_{e, out} \), and the mass of the mixtures is \( m_{mix} \), the energy \( Q_{mix} \) can be described as:

\[
Q_{mix} = m_{mix} c_p \left( T_{e, in} - T_{e, out} \right)
\]

(2)

The water vapour contains a large amount of energy in the form of latent heat, which is the main objective to use in the gases. The energy of the vapour which can be used is:

\[
Q_w = m_w (h_{vap} - h_w)
\]

(3)

\( h_{vap} \) is the specific enthalpy of the vapour, and \( h_w \) is the specific enthalpy of the water. \( m_w \) is the mass of vapour which turns to water after heat exchange. Hence the total energy used of the waste gas is:

\[
Q_{use} = Q_{mix} + Q_w
\]

(4)

It is common to evaluate the energy utilization of the asphalt plant by the production of 1 ton HMA. So \( m_{mix} \) and \( m_w \) represent the mass of the gas when 1 ton HMA is produced.

The output power of the electricity in the system can be described as:

\[
P_{out} = \dot{m}_{med} (h_1 - h_2) \eta_i
\]

(5)

\( \dot{m}_{med} \) is the mass flow rate of the fluid. \( h_1 \) is the specific enthalpy at the entrance of the expander while \( h_2 \) is at the exit. \( \eta_i \) is the efficiency of the energy transferred from the shaft to the generator.

\[
h_2 = h_1 - \left( h_1 - h_{2s} \right) \eta_i
\]

(6)

\( h_{2s} \) is the specific enthalpy during the constant entropy process. \( \eta_i \) is the internal efficiency of the expander.

The system efficiency is:

\[
\eta_{sys} = \frac{P_{out}}{P_{in}}
\]

(7)

\( P_{in} \) is the power gained from the heat source.

\[
P_{in} = k \cdot P_{use}
\]

(8)

\( k \) is the heat transfer efficiency of the evaporator.

3.2. Energy analysis

The ORC system should be designed based on the production process of the asphalt plant. Hence the data were used to analyse the system energy. The data in Table1. are cited from [2]. If the waste heat of the gases was used from 110℃ to 60℃, the energy utilization is considerable.

| Performance parameter            | Value  |
|----------------------------------|--------|
| Energy consumption /MJ           | 227.21 |
| Mass of dry gases /kg            | 176.76 |
| Mass of the vapour /kg           | 5.85   |
| Exhaust gas temperature /℃       | 110    |
| Environmental temperature /℃     | 20     |
Outlet temperature of the exchanger/°C 60
Energy available in the exhaust gases/MJ 23.43
Energy used in the exhaust gases/MJ 23.23

It is shown that the energy in the exhaust gases is 10.2% of the total energy consumed. The energy used in the ORC system occupies most part of the energy available in the gases. It is obvious that the latent energy of the vapour is the core of the gases.

4. Results and discussion

JD3000 with the production of 240 tons per hour is a common type asphalt plant. Its power consumption is about 610kW. The fuel used could achieve 1500kg per hour. If it is combined with the ORC system designed above, the parameters and energy consumption is shown in Table 2.

Table 2. Energy analysis of the system with the production of HMA 240 t·h⁻¹

| Performance parameter                  | Value |
|----------------------------------------|-------|
| Production of HMA /t·h⁻¹               | 240   |
| Evaporation temperature /°C            | 80    |
| Condensation temperature /°C           | 25    |
| Inlet temperature of the expander /°C  | 90    |
| Temperature after condensation /°C     | 23    |
| Mass flow rate of the fluid /kg·s⁻¹    | 5.71  |
| Expander efficiency /%                 | 60    |
| Generator efficiency /%                | 95    |
| Output power/ kW                       | 104.4 |
| System efficiency of ORC system /%     | 7.5   |

Table 2 shows it will generate 104.4kW of electricity for the combined ORC system. And if the electricity is used to the production process, it will save 17.1% of power. For instance, when 200 thousand tons of HMA is produced for JD3000, 87000kwh will be saved. It is obvious that the energy saving effect is considerable.

However the system efficiency is only 7.5%, which is not high. According to the Carnot's theorem, the system efficiency is related to the maximum temperature of the heat source and minimum temperature of the cold source. In this system the ideal and highest engine efficiency is only 23.5%. The low temperature of the gases result in the low system efficiency. Another significant reason is the heat lost of the exhaust gas after expansion. Improve the design level of expansion machine is a good way to increase the efficiency. Adding a recuperator can enhance the efficiency too, but it will increase the system complexity.

5. Conclusion

This paper investigated an ORC system for the waste heat recovery of asphalt plant. The heat source properties and the influence factors were analyzed. An ORC that uses the heat from the waste gases of the rotary dryer and generates electric power was developed. Thermodynamic design and performance analysis of the ORC system were conducted. Because the critical temperature of R245fa is close to the initial temperature of the heat source and the expansion ratio is moderate, R245fa was selected as the working fluid for the ORC system in this paper. The evaporator which could support phase-change heat transfer was selected. Meanwhile the radial inflow turbine was chosen.

The data from the asphalt plant were taken to analyze the potential of energy utilization. It could generate 104.4kW electricity if the ORC system designed is used for JD3000 asphalt plant. If the electricity is used to the plant, 17.1% of electricity power could be saved. The economic value is considerable in the long term because the asphalt plant usually runs many years and has large production.

A new method with ORC system was proposed for the waste heat recovery of the asphalt plant. The system developed in this study may serve as guides for the further research. Further work will be conducted with a view to increasing overall cycle efficiency by increasing turbine efficiency, reducing
heat loss in the flow path, and optimizing the system layout and components such as heat exchangers and a pump. Furthermore, the evaporator must be investigated deeply to match the system.

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