Research on the energy and ecological efficiency of mechanical equipment remanufacturing systems

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Abstract. According to the characteristics of mechanical equipment remanufacturing system, the dynamic performance of energy consumption and emission is explored, the equipment energy efficiency and emission analysis model is established firstly, and then energy and ecological efficiency analysis method of the remanufacturing system is put forward, at last, the energy and ecological efficiency of WD615.87 automotive diesel engine remanufacturing system as an example is analyzed, the way of energy efficiency improvement and environmental friendly mechanism of remanufacturing process is put forward.

1. Introduction

Compared with traditional manufacturing of mechanical equipment, there is a series of complex and uncertain characteristics in the mechanical equipment remanufacturing system, such as energy consumption source, material flow, emissions involved, process and changed dynamic state. Therefore, it is a challenge to explore the energy and ecological efficiency of remanufacturing system. This paper puts forward an analysis method of energy and ecological efficiency of remanufacturing system for typical remanufacturing equipment and process. Furthermore, the method of efficiency improving and environmental friendly mechanism is put forward.

2. Analysis method of the energy and ecological efficiency of remanufacturing systems

The typical process of mechanical equipment remanufacturing includes: disassembly, cleaning, testing, repairing and assembly[11]. Because there are differences of process technology and equipment due to the different damage of old parts, the energy and material consumption are different also. In this study, the energy and ecological efficiency is analyzed based on the consumption of energy and material of the remanufacturing system. The analysis model is shown in Figure 1.

Where, \( E_i(j=1,2...5) \) is the input energy of the equipment system, \( E_o(j=1,2...5) \) is the lost energy, \( E_{eo}(j=1,2...5) \) is the efficient energy. \( M_i(1,2...5) \) is the input materials, \( M_o(1,2...5) \) is the lost materials, \( M_{eo}(1,2...5) \) is the efficient used materials.
Figure 1. Energy and ecological efficiency analysis model of remanufacturing system

2.1. Energy efficiency analysis method

Energy consumption of the mechanical equipment remanufacturing system mainly includes: energy consumption in the process of startup, working, standby, and losses. Therefore, the energy calculation model is as equation (1):

\[
E_{input} = \sum_{i=1}^{Q_i} E_{si} + \sum_{j=1}^{Q_j} E_{uj} + \sum_{k=1}^{Q_k} E_{mk} + \sum E_{lost} 
\]  

(1)

Where, \( E_{input} \) is the input energy, \( E_{si} \) is the consumed energy of the \( i \)th startup process, \( Q_i \) is the frequency of startup, \( E_{uj} \) is the consumed energy of \( j \)th standby process, \( Q_j \) is the frequency of standby, \( E_{mk} \) is the consumed energy of \( k \)th working process, \( Q_k \) is the frequency of working, \( E_{lost} \) is the lost energy.

Energy efficiency indicator is expressed as the ratio of effective energy to the total input energy (or be expressed as specific energy consumption) in working process, shown in equation (2):

\[
EN = \frac{E_{Ec}}{E_{input}} = \frac{\sum_{k=1}^{Q_k} E_{mk}}{E_{input}} 
\]  

(2)

Where, \( EN \) is energy efficiency, \( E_{Ec} \) is the effective energy in working process, \( E_{input} \) is the total input energy of remanufacturing system.

2.2 Ecological efficiency analysis method

As shown in figure 1, in this study, material and energy flow is comprehensively considered, and by means of LCA (Life Cycle Assessment) method and CLCD (Chinese Core Life Cycle Database), environmental emissions is expressed by material consumption and energy consumption integrated, shown as equation (3):

\[
P_i = \sum_{m} f_{im} E_m + \sum_{j} f_{ij} M_j 
\]  

(3)

Where, \( P_i \) is the \( i \)th environmental emissions, \( E_m \) is the \( m \)th energy consumption, \( M_j \) is the \( j \)th material consumption, \( f_{im} \) and \( f_{ij} \) is respectively represent the emission factor of \( m \)th energy and \( j \)th material consumption.

By equation (3), the energy flow and the material flow are integrated into the ecological efficiency analysis. The ecological efficiency is measured in broad measurement, which is given in equation (4)
Where, $EO_i$ is the ecological efficiency indicator, $V$ is the value or amount of product, which can be shown as the form of product output, sales volume, profit, etc, $EI_i$ is the $ith$ environmental impact potential, which can be expressed as global warming potential, acidification potential, etc.

According to the life cycle inventory of input information (material and energy consumption), referred to CLCD database, the resource consumption and environmental emissions (such as CO$_2$, CFCs, SO$_2$, etc.) can be get, and after classification, characterization, normalization and weights\textsuperscript{[4-5]}, the environmental impact potential index $EI$ is obtained, given in equation (5):

$$EI = \sum_{j=1}^{m} V_k \times \left( \frac{\sum_{i=1}^{n} EK_i \times G_i}{R_k} \right)$$

Where, $G_i$ is the amount of the $ith$ substance in the inventory, $EK_i$ is the environmental characterization indicator of the $ith$ substance, $R_k$ is the $kth$ environmental normalization indicator, $V_k$ is the weight of the $kth$ environmental indicator.

3. Case study

Take the WD615.87 diesel engine remanufacturing system for example, when the old machine is recycled, it will go through the processed as: disassembly -- cleaning -- testing -- repairing -- assembly. From investigation, the disassembly and assembly devices are usually pneumatic wrenches and wind triggers, the cleaning device is ZQX-135 cleaning machine, the testing device is CEW2001 magnetic inspection machine, and the repair devices is CMD-AS arc spraying machine and automatic nanobot plating equipment\textsuperscript{[6]}. The energy and material consumption of the engine remanufacturing is shown in table 1.

| Item | Process | Disassembly | Clean | Test | Repair | Assembly | Total |
|------|---------|-------------|-------|------|--------|----------|-------|
| Energy (Kwh) | $E_{xi}$ | 0.5 | 2.5 | 0.5 | 5.4 | 0.7 | 9.6 |
|         | $E_{xj}$ | 1.1 | 3.4 | 0.2 | 5.9 | 1.1 | 11.7 |
|         | $E_{mk}$ | 18.9 | 175.2 | 16.1 | 200.5 | 48.9 | 459.6 |
|         | $E_{lost}$ | 0.2 | 1.9 | 0.2 | 5.2 | 0.3 | 7.8 |
|         | $E_{input}$ | 20 | 183 | 17 | 217 | 51 | 488 |
| Material (kg) | Iron | / | / | / | 10.10 | / | 10.10 |
|         | Alloy | / | / | / | 9.40 | / | 9.40 |
|         | Aluminum | / | / | / | 12.10 | / | 12.10 |
|         | Kerosene | 2.00 | 7.02 | / | / | / | 9.02 |
|         | Diesel | 3.00 | 8.50 | / | / | / | 11.50 |

3.1 Energy efficiency analysis

According to Table 1 and Equation (1)–(2), the total energy efficiency of engine remanufacturing is known as:

$$EN = \frac{E_{c}}{E_{st}} = \frac{\sum_{k=1}^{Q_{st}} E_{mk}}{E_{input}} = \frac{459.6 \times 100\%}{488} \approx 94.1\%$$

By the same way, the disassembly energy efficiency is 94.5%, the cleaning energy efficiency is 95.7%, the testing energy efficiency is 94.7%, the repairing energy efficiency is 92.3%, and assembly energy efficiency is 95.9%.
It is clearly that the highest energy efficiency is in the cleaning process, the lowest energy efficiency is in repairing phase, the reason for this situation is that there are a lot of uncertainties of old parts damage conditions (such as crack, fatigue or wear), and the repairing process and device will be different due to different damage conditions, sometimes there are presence of miscalculation for the damage condition and wrong process and device are selected, which make the lower energy efficiency. Therefore, in old parts repairing phase, it is necessary to pay attention to the specific damage and appropriate repairing process and devices selection. Also repairing transformation plan should be well designed and unnecessary energy waste are avoided.

3.2 Ecological efficiency analysis

3.2.1 Environmental impact analysis. According to ISO 14042\(^7\), environmental impact potentials of CRDP (Chinese Resource Depletion Potential), GWP (Global Warming Potential) and AP (Acidification Potential) are selected. In which, CRDP is determined mainly by coal, oil, natural gas, iron, aluminum and other non-renewable resources and energy, GWP is determined by the emissions of \(\text{CH}_4\), \(\text{CO}_2\), \(\text{CO}\), \(\text{NO}_x\), etc, \(\text{SO}_2\), \(\text{NO}_x\), \(\text{H}_2\text{S}\), HCL and other gases determine the potential of AP\(^8\). According to equation (3) and (5), the engine remanufacturing inventory and the results of characterization and normalization are shown in table 2.

| Classification | Inventory | Amount (kg) | Characterization factor | Characterization result | Normalization factor | Normalization result |
|----------------|-----------|-------------|-------------------------|-------------------------|---------------------|---------------------|
| CRDP           | Iron      | 22.1        | 4.45                    | 2607.05                 | 0.66                | 1667.05             |
|                | Aluminum  | 12.05       | 2.88                    |                         |                     |                     |
|                | Coal      | 582.21      | 1                       | 3959                    | 0.39                | 233.34              |
|                | Petroleum | 68.58       | 26.4                    |                         |                     |                     |
|                | Natural gas | 6.35      | 12.8                    |                         |                     |                     |
| GWP            | \(\text{CO}_2\) | 1033.63  | 1                       | 1854.12                 | 0.21                | 549                |
|                | \(\text{CH}_4\) | 3.68      | 25                      |                         |                     |                     |
|                | \(\text{NO}_x\) | 3.20      | 320                     |                         |                     |                     |
|                | CO         | 12.56      | 2                       |                         |                     |                     |
| AP             | \(\text{SO}_2\) | 11.49     | 1                       | 14.05                   | 0.39                | 5.53               |
|                | \(\text{NO}_x\) | 2.20      | 0.7                     |                         |                     |                     |
|                | \(\text{H}_2\text{S}\) | 0.43      | 1.88                    |                         |                     |                     |
|                | HCL        | 0.25       | 0.88                    |                         |                     |                     |

It is known that the weight of CRDP is 0.74, GWP 21.6 and AP 0.05, therefore, the comprehensive environmental impact potential is calculated as:

\[
EI = 0.66 \times 0.74 + 0.21 \times 21.6 + 0.39 \times 0.05 = 5.04
\]

3.2.2 Ecological efficiency analysis. In this study, \(V\) is the profit of a remanufactured engine, \(EI\) is the comprehensive environmental impact potential, the profit of a remanufactured engine is 2000 yuan RMB, according to equation (4), the ecological efficiency of each environmental impact potential is:

\[
EO_{\text{CRDP}} = \frac{0.66}{0.2} \approx 3.3, \quad EO_{\text{GWP}} = \frac{0.21}{0.2} = 1, \quad EO_{\text{AP}} = \frac{0.39}{0.2} \approx 1.95
\]

Comprehensive ecological efficiency is:
From the result it can be conclude that, each 10000 yuan RMB of engine remanufacturing profit will produce 25.2 units comprehensive environmental impact potential, and produce 3.3, 1 and 1.95 environmental impact potential of CRDP, GWP and AP respectively. It is illustrated that the engine remanufacturing produces lower environmental impact of greenhouse effect, and more Chinese resource consumption. Although the engine remanufacturing saves resources, however, compared with other environmental impact, it is also necessary to search measures of reducing resources and energy input, especially electricity, which would reduce large environmental impact of CRDP, GWP and AP at the same time, because the electricity production will produce large amount of CO₂ and SO₂.

4 Conclusion

Based on the analysis of energy and materials consumption and environmental emissions of the remanufacturing system, energy and ecological efficiency analysis method for remanufacturing system is presented. The WD615.87 diesel engine remanufacturing as an example is used to demonstrate and verify the effectiveness of this method. The research results could provides basic theory and method of energy efficiency and environmental emissions dynamic characteristics for the remanufacturing system analysis, which with important research significance and application value.

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