



Research article

Research on thermoeconomic fault diagnosis for marine low speed two stroke diesel engine

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Abstract: To satisfy the requirements of low fuel consumption, low emission, and high efficiency of the shipping industry, marine diesel engines are developing in the direction of automation and energy-saving, which increases the possibility and complexity of marine diesel engine failures. A one-dimension thermodynamic model for the marine diesel engine is built with AVL Boost software. The model is applied to a low-speed two-stroke 6S50MC diesel engine, and the error between the main performance parameters obtained by simulation and the test bench data is less than 3% under 100% and 75% load. Based on the model, 6 typical single faults and many typical double faults concomitant phenomena of diesel are reproduced. Based on the second law of thermodynamics, the exergy flow among the components and the external environment is analyzed. The thermoeconomic model of a marine diesel engine is established where the "fuel" and "product" of the components are defined according to their function. The fault diagnosis results show that the effects of faults generally propagate through the diesel engine system and affect the behavior of several components, resulting in induced malfunction in normal components. Therefore the malfunction MF_i of each component is the superposition of the intrinsic malfunction and the induced malfunction according to the malfunction and dysfunction analysis. The thermoeconomic fault diagnosis method can be used to narrow the search range of abnormal components though it cannot accurately locate the fault.

Keywords: marine diesel; fault simulation; thermoeconomic; fault diagnosis; malfunction

Abbreviation: IMEP (Indicated Mean Effective Pressure(bar)), LHV (Lower Heating Value (J/kg)), Δ (Increment), ϕ (Irreversibility coefficient), ω (External plant product), DF (Dysfunction generated in a component (kW)), C1 (Air compressor), C2 (Air cooler), C3 (Intake air manifold), C4~C9 (Cylinder 1~6), C10 (Exhaust manifold), C11

(Turbine), E_{xa} (air exergy flow (kW)), E_{xg} (exhaust gas exergy flow (kW)), F (Fuel exergy of a component (kW)), I (Irreversibility of a component (kW)),

k (Specific exergy consumption(-)), MF (Malfunction of a component (kW), n (Number of components), P (Product exergy of a component (kW)), W_T (power provided by the turbine (kW)),

W (output power of cylinder (kW)), i, j (Index for numerating of components or exergy flows), tot (Total plant)

1. Introduction

As the main power of ship propulsion, the marine diesel engine is also the core equipment of the ship power plant. Ocean transportation puts forward the requirements of low consumption, low emission, and high efficiency for ships. Marine diesel engines are constantly developing towards automation and energy saving. The working performance is continuously improved and the degree of automation is getting higher and higher, but at the same time, the maintenance and overhaul of the ship's main engine have also increased greatly, thus increasing the possibility and complexity of failure.

In addition, the marine diesel engine is a very complicated system due to the existence of the turbocharger and all the other subsystems. These engines have a lot of advantages, including high efficiency, high power concentration, and long operational lifetime [1,2]. Although the efficiency of marine diesel engines is very important, the priority of reliability is higher to maximize the safety of ships.

A failure in the marine diesel engine will threaten the safety of the crew. In recent years, to improve the reliability of the marine diesel engine, the maintenance of the marine diesel engine is developing in the direction of predictive actions [3].

The research shows that the diesel engine system is nonlinear, and the diesel engine system failures are caused by many factors. A diesel engine system contains many subsystems, which influence each other.

During the working process of the diesel engine, due to factors such as wear, fatigue, aging and other factors of a certain subsystem, the operating state of other subsystems will be changed, and the characteristics of the fault will be distorted during the propagation process. In addition, there is more than one propagation path. Resulting in a phenomenon that a source of failure may be manifested as a failure of multiple subsystems.

Therefore, the failure source and the failure manifestation are not a simple one-to-one mapping relationship. It may happen that one fault source corresponds to multiple fault manifestations, but also that multiple fault sources correspond to one fault manifestation, and multiple failure sources correspond to the cross-coupling phenomenon of multiple failure manifestations. In summary, diesel engine failure has the characteristics of propagation, coupling, and unknowability.

Engineers usually use measurable parameters such as exhaust temperature and cylinder pressure diagrams to test the performance of marine diesel engines. These parameters are affected by the characteristics of diesel engines, and in most cases, it is difficult to determine the cause of failure [4,5].

Thermoeconomics is a technology based on the second law of thermodynamics. A·Valero [6,7] proposed the concepts of "Fuel" and "Product" and established a general model based on this.

The resource consumed by each component is defined as fuel, and its useful output is defined as a product. The loss caused by irreversibility is called irreversible loss. Based on cost balance and appropriate cost allocation rules [8], which allows the analyst to disaggregate the additional fuel consumption into contributions associated with the malfunctions occurring in each specific component, to determine the main cause of performance degradation. Thermal economy diagnosis has high theoretical potential, but in most applications, it is difficult to obtain effective results. Because the change of one component in the system will affect all components in the system through the interaction of mass flow and energy flow, and affect the parameters of other components.

Therefore, the true origin of the malfunction is likely to be obscured by all the consequent induced effects. The direction towards an effective diagnostic procedure should be able to distinguish between intrinsic and induced effects [9–12].

In the present work, thermoeconomic faults diagnosis of diesel engine is a pioneeristic approach to detect single or multiple faults and quantify their impact in terms of additional energy consumption. The thermoeconomic fault diagnosis describes the propagation phenomenon of faults in the diesel engine system from the perspective of the second law of thermodynamics, and could be used to solve the problem of diesel engine fault diagnosis in complex situations. The thermal economics fault diagnosis method can effectively narrow the search range of abnormal components, in addition, the method can accurately quantify the economic loss caused by the failure, and provide a basis for ship health management.

2. Methodology

2.1. The engine simulation model

To guarantee a good response and an accurate model, especially when failures are introduced, a one-dimensional wave action model is constructed using AVL Boost, which is widely used by the scientific community [13–18].

The simulation model of the MAN 6S50 MC-C8.1 diesel engine was built with AVLBoost© v2020, Table 1 shows the general characteristics of the marine diesel engine. The diesel engine consists of 6 cylinders in line with a rated power of 9960 kW @ 127 rpm. A turbocharger boost air pressure in the constant pressure air manifolds. The air that comes from the compressor is mixed and cooled in the air cooler before the air manifold. A constant pressure exhaust gas manifolds from which the gas flows into the turbines.

Table 1. Specification of diesel engine.

| Parameters | Values |
|-----------------------|--------------------------|
| Rated power | 9960 kW |
| Rated speed | 127 rpm |
| Number of cylinders | 6 |
| Cylinder bore | 500 mm |
| Stroke | 2000 mm |
| Connecting rod length | 2050 mm |
| Displacement volume | 0.39 m ³ |
| Compression ratio | 21:1 |
| Turbocharger type | TCA66-21*2 |
| Bypass valve diameter | 61 mm |
| LHV | 4.292×10^7 J/kg |
| Fire order | 1-5-3-4-2-6 |

2.2. Model validation

The engine shop test is used in validation, which is obtained from the data report of the official shop trials. Validation of the model is carried out by comparing simulation and experimental main parameters mean values.

Table 2. Comparison between simulated and experimental mean values.

| Engine load Parameter | 100% | | | 75% | | | 50% | | |
|-------------------------------------|----------|-----------|--------|----------|-----------|---------|----------|-----------|---------|
| | Measured | Simulated | Error% | Measured | Simulated | Error % | Measured | Simulated | Error % |
| Power(kW) | 9960.0 | 9993.26 | 0.33 | 7472.4 | 7546.3 | 0.99 | 4980.0 | 4568.7 | -8.26 |
| P _{BOOST} (bar) | 4.00 | 3.96 | -1.00 | 3.15 | 3.08 | -2.16 | 2.27 | 2.07 | -8.95 |
| Compressor Outlet Temperature (K) | 475.28 | 475.2 | -0.02 | 435.72 | 436.64 | 0.21 | 393.80 | 378.56 | -3.87 |
| Air Mass Flow (kg/s) | 25.22 | 24.71 | -2.03 | 19.69 | 19.03 | -3.36 | 13.81 | 12.38 | -10.33 |
| Air Cooler Outlet Temperature (K) | 310.41 | 309.90 | -0.16 | 307.64 | 308.24 | 0.19 | 304.71 | 293.65 | -3.63 |
| Air Manifold Temperature (K) | 334.30 | 320.20 | -4.22 | 331.99 | 318.51 | -4.06 | 329.55 | 301.56 | -8.49 |
| IMEP (bar) | 20.00 | 20.05 | 0.25 | 16.51 | 16.68 | 1.01 | 11.45 | 10.50 | -8.28 |
| Turbocharger Inlet Temperature (K) | 679.77 | 695.04 | 2.25 | 649.18 | 661.80 | 1.94 | 669.88 | 628.28 | -6.21 |
| Turbocharger Inlet Pressure (bar) | 3.75 | 3.73 | -0.53 | 2.81 | 2.77 | -1.48 | 575.10 | 562.23 | -2.24 |
| Turbocharger Outlet Temperature (K) | 518.93 | 528.60 | 1.86 | 520.87 | 540.57 | 3.78 | 1.98 | 1.82 | -7.92 |

Table 2 shows a comparison between mean values of performance and representative thermodynamic variables provided by simulation with respect to those measured in the test bench. Table 2 indicates that the model simulates engine behavior with good precision. The difference between simulation and experimental values is less than 5%, although less precision in some parameters for low load operating points.

Therefore, it is considered that the model is adjusted and validated satisfactorily, so it can be used as a failure simulation platform without the need to produce them in a real diesel engine.

2.3. Failure simulation

Once the model has been adjusted and validated, failures are introduced one by one. The term “failure” here is intended as “soft failure”, that is, a fault that only causes equipment performance degradation, but does not cause the component to stop operating.

The one-dimensional diesel engine model built in this paper considers the influence of wave dynamics on the mass flow of the cylinder, and each failure is realized through a series of reasonable modifications to the parameters that define the fault. The relevant work of the two-stroke diesel engine fault simulator can be found in [19–23].

2.3.1. Air compressor failure

The compressor failure is usually caused by dust accumulation in the impeller or diffuser as well as damages that produce changes in geometry. The compressor failure is simulated by reducing the isentropic efficiency and the air mass flow rate (-5%, -10%, -15%) of the compressor.

2.3.2. Air cooler failure

The air cooler failure is usually caused by the increase of fouling on the inner wall of the air cooler, which will produce an excessive pressure drop and a reduction of cooling capacity. The air cooler failure is simulated by reducing the isentropic efficiency (-5% , -10% , -15%) and increasing the inlet and outlet pressure variation of the air cooler.

2.3.3. Intake air manifold leakage

The failure of the intake manifold is usually due to the lack of sealing by cracks in material or pipe joints connected to the air intake manifold. A 20 mm diameter tube is created without restrictions in the intake manifold open to the atmosphere. The value of the discharge coefficient of this tube is respectively (0.1, 0.2, 0.4) .

2.3.4. Cylinder failure: (the combustion duration extended)

This kind of cylinder failure is usually caused by the fault of the fuel injection system or the carbon accumulation of the nozzle, which will lead to poor fuel atomization and combustion performance. Modify the combustion duration angle in the double vibe law of cylinder 1, by adding 5° , 10° and 15° respectively to simulate this failure.

2.3.5. Exhaust manifold leakage

The failure of the exhaust manifold is usually due to the lack of sealing by cracks in material or pipe joints connected to the exhaust manifold. A 20 mm diameter tube is created without restrictions in the exhaust manifold open to the atmosphere. The value of discharge coefficient of this tube is respectively (0.1, 0.2, 0.4) .

2.3.6. Turbine failure

The turbine failure is usually caused by dust accumulation in the impeller or diffuser as well as damages that produce changes in geometry. The turbine failure is simulated by reducing the isentropic efficiency and the air mass flow rate (-5% , -10% , -15%) of the turbine.

2.4. Fundamentals of thermoeconomic diagnosis

An important concept in structural theory is “fuel” and “product”. Valero proposed that “fuel” and “product” generally refer to the input and output of a subsystem; there will be irreversible loss in the actual process, a certain amount of exergy loss will occur. Using the concept of fuel and product, the exergy balance formula a component is:

$$F = P + I \quad (1)$$

where, F : fuel; P : product; I : irreversible loss.

2.4.1. Unit exergy consumption

We define the unit exergy consumption as the number of exergy units that each component requires from the production of the rest of the components, to obtain an exergy unit of its product:

$$k = \frac{F}{P} \quad (2)$$

where k is unit exergy consumption.

The sum of the exergy unit consumptions related to each component is the inverse of exergy efficiency η_j .

$$k_j = \sum k_{ij} = \sum \frac{F_{ij}}{P_j} = \frac{F_j}{P_j} \quad (3)$$

Therefore, the production relationship of each component can be expressed as:

$$P_i = P_{0,i} + \sum_{j=1}^n k_{ij} P_j, \quad i=0, 1, \dots, n \quad (4)$$

where, P_i is the product of the i th component, $P_{0,i}$ represents the final production of the component i , k_{ij} represents the portion of the i th component production needed to get a unit of the j th component production.

According to the concept of “fuel” and “product”, the unit exergy consumption of each component can be obtained, as shown in Table 3.

Table 3. Unit exergy consumption of each component.

| Component | Fuel | Product | k |
|---------------------|---|---|--|
| Compressor | $W_T + E_{xa1}$ | E_{xa2} | $k_1 = \frac{W_T + E_{xa1}}{E_{xa2}}$ |
| Air cooler | E_{xa2} | $E_{xa3} + E_{XQ1}$ | $k_2 = \frac{E_{xa2}}{E_{xq1} + E_{xa3}}$ |
| Intake air manifold | E_{xa3} | $E_{xa4} + E_{xa5} + E_{xa6} + E_{xa7} + E_{xa8} + E_{xa9}$ | $k_3 = \frac{E_{xa2}}{E_{xa4} + E_{xa5} + E_{xa6} + E_{xa7} + E_{xa8} + E_{xa9}}$ |
| Cylinder 1 | $E_{xf1} + E_{xa4}$ | $W_1 + E_{xg1}$ | $k_4 = \frac{E_{xf1} + E_{xa4}}{W_1 + E_{xg1}}$ |
| Cylinder 2 | $E_{xf2} + E_{xa5}$ | $W_2 + E_{xg2}$ | $k_5 = \frac{E_{xf2} + E_{xa5}}{W_2 + E_{xg2}}$ |
| Cylinder 3 | $E_{xf3} + E_{xa6}$ | $W_3 + E_{xg3}$ | $k_6 = \frac{E_{xf3} + E_{xa6}}{W_3 + E_{xg3}}$ |
| Cylinder 4 | $E_{xf4} + E_{xa7}$ | $W_4 + E_{xg4}$ | $k_7 = \frac{E_{xf4} + E_{xa7}}{W_4 + E_{xg4}}$ |
| Cylinder 5 | $E_{xf5} + E_{xa8}$ | $W_5 + E_{xg5}$ | $k_8 = \frac{E_{xf5} + E_{xa8}}{W_5 + E_{xg5}}$ |
| Cylinder 6 | $E_{xf6} + E_{xa9}$ | $W_6 + E_{xg6}$ | $k_9 = \frac{E_{xf6} + E_{xa9}}{W_6 + E_{xg6}}$ |
| Exhaust manifold | $E_{xg1} + E_{xg2} + E_{xg3} + E_{xg4} + E_{xg5} + E_{xg6}$ | E_{xg7} | $k_{10} = \frac{E_{xg1} + E_{xg2} + E_{xg3} + E_{xg4} + E_{xg5} + E_{xg6}}{E_{xg7}}$ |
| Turbine | E_{xg7} | $W_T + E_{xg8}$ | $k_{11} = \frac{E_{xg7}}{W_T + E_{xg8}}$ |

The fuel/product diagram is shown in Figure 1. we can see the chosen disaggregation scheme of the system. For each component it is shown the portion of its product which is consumed (as a fuel) by other plant devices.

In Figure 1, W_T represents the power provided by the turbine; E_{xa1} represents air exergy flow at compressor inlet; E_{xa2} represents air exergy flow at compressor outlet; E_{xa3} represents air exergy flow at the exit of air cooler; E_{xa4} – E_{xa9} represents air exergy flow at the inlet of cylinder 1~6; W_1 – W_6 represents the output power of cylinders 1~6; E_{xg1} – E_{xg6} indicates exhaust gas exergy flow of cylinders 1~6; E_{xg7} represents exhaust gas exergy flow at turbine inlet; E_{xg8} means exhaust gas exergy flow at turbine outlet; ExQ_1 stands for exergy loss of air cooler.

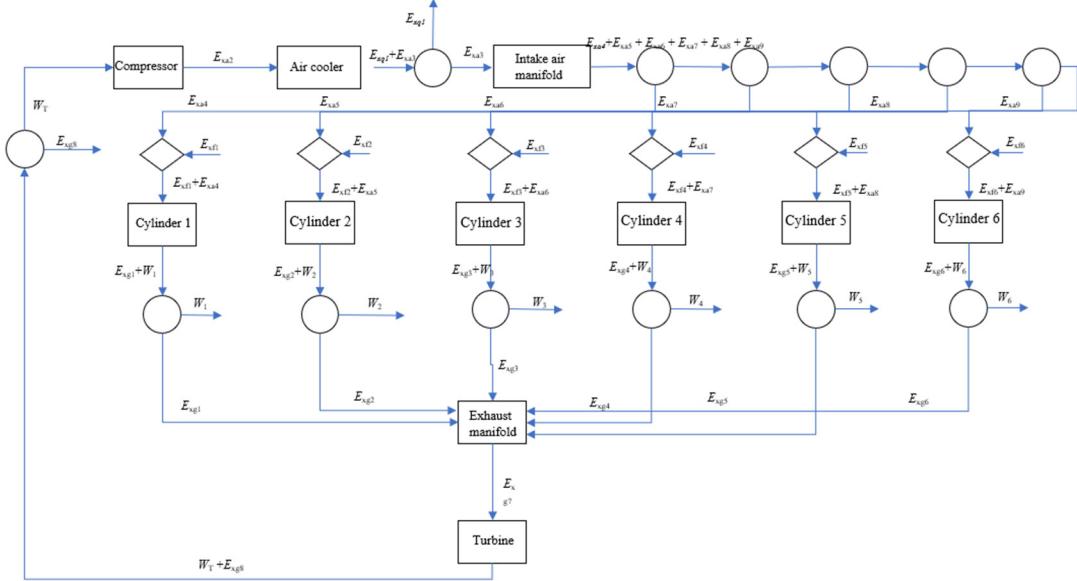


Figure 1. The fuel/product diagram.

2.4.2. “Fuel impact” formula

The fuel impact formula was first proposed in [24] and further developed in [25–27]. The fuel impact formula evaluates the “contribution” given by the malfunctioning component the i th to the variation of the total plant fuel consumption F_{tot} .

In a productive structure represented by components having a single product and one or, more entering resources fuels, the fuel impact formula is expressed in finite terms as :

$$\Delta F_{tot,i} = \sum_{i=1}^n \left(\sum_{j=0}^n k_{P,j} \Delta k_{ji} \right) P_i + \sum_{i=1}^n k_{P,i} \Delta \omega_i \quad (5)$$

where P_i is the product of the i th component in the reference condition, $k_{P,j}$ is the unit exergetic cost of the product P_j of the j th component which enters as resource E_{ji} in the i th one, k_{ji} is the variation between reference and operating conditions of the unit energetic consumption of this resource due to the malfunction, and i is the variation of the overall plant production between reference and operating conditions due to the i th component.

Assuming that the total product is constant, then equation 6 can be expressed as:

$$\Delta F_{tot,i} = \sum_{i=1}^n \left(\sum_{j=0}^n k_{P,j} \Delta k_{ji} \right) P_i \quad (6)$$

2.4.3. Malfunction and dysfunction

While the remaining part is due to the variation of component product, Valero et al[24] separated the irreversibility variation into the two terms ΔI_k and ΔI_P .

$$\Delta I = \Delta I_{\Delta k} + \Delta I_{\Delta P} = \Delta k P + (k-1) \Delta P \quad (7)$$

Research shows that the same amount of additional irreversible loss occurs in different components of the system, and the additional resources required to keep the final output product of the system unchanged are not the same [28–29].

ΔI_k and ΔI_P are parts of the total irreversibility variation of the i th component. ΔI_k was defined in [30] as malfunction, which is caused by the change of unit exergy consumption of the component itself. ΔI_P was defined in [30] as dysfunction which is induced in the i th component by the malfunctions of the other components and consists of a variation of resources caused by the variation of product P_i required by the other components.

$$MF_i = \Delta k_i P_i = \sum_{j=0}^n \Delta k_{ji} P_i = \sum_{j=0}^n MF_{ji} \quad (8)$$

$$DF_i = \sum_{j,h=1}^n \varphi_{ih} \Delta k_{hj} P_j + \sum_{j=1}^n \varphi_{ij} \Delta \omega_j \quad (9)$$

The coefficient φ_{ij} the irreversibility generated in the j th component to obtain a unit of the i th product. According to the definition, DF_i cannot represent the intrinsic cause of the total fuel variation.

3. Results and discussion

Thermoeconomic diagnosis is widely used in thermal power plants and gas turbines, etc., but the thermoeconomics research on fault diagnosis of marine diesel engine systems is still in its infancy. The marine diesel engine system is non-linear. The marine diesel engine can be regarded as a large system containing multiple subsystems, and each subsystem has some different degrees of influence on each other. During the operation of the diesel engine, the wear, fatigue, and aging of its components cause failure and deterioration of the system, and also lead to changes in the causal relationship between the various subsystems.

The fault characteristic information of the system will be distorted in the process of transmission. In addition, the transmission path of the fault characteristic information is more than one, which implies that the fault diagnosis of the diesel engine system is a highly complex and difficult task.

3.1. Diagnosis results under single fault conditions

After the engine model has been validated and the 6 most typical thermodynamic failures are introduced, the fault simulation results are imported into the thermoeconomic model, and compared with the thermoeconomic control group (by reducing the diesel engine speed and circulating fuel injection to keep the same production), the irreversibility variation of each component of the diesel engine system can be obtained. The increased irreversibility variation can be divided into two parts. The analysis of the malfunction is more important, because the malfunction is caused by the change of the component efficiency, and the change of the component efficiency directly affects the performance of the component. The result is shown in Tables 4–9.

Table 4. Air compressor failure.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|---------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 198.83 | 109.31 | 483.64 | 260.29 | 775.01 | 407.56 |
| C2 | 102.37 | 46.11 | 230.84 | 100.38 | 385.82 | 161.42 |
| C3 | -0.84 | -3.83 | -17.27 | -7.65 | -26.82 | -11.46 |
| C4 | 81.79 | 51.07 | 174.69 | 107.87 | 275.56 | 167.64 |
| C5 | 82.24 | 51.35 | 174.69 | 107.87 | 275.57 | 167.63 |
| C6 | 81.79 | 51.07 | 174.69 | 107.87 | 275.56 | 167.63 |
| C7 | 82.24 | 51.36 | 173.35 | 107.07 | 272.82 | 166.05 |
| C8 | 78.64 | 49.12 | 169.73 | 104.87 | 268.75 | 163.63 |
| C9 | 18.56 | 51.36 | 37.94 | 107.07 | 57.71 | 165.78 |
| C10 | -28.75 | -21.67 | -56.00 | -41.91 | -89.24 | -66.09 |
| C11 | -80.87 | -52.83 | -186.57 | -122.22 | -274.55 | -179.56 |

Table 5. Air cooler failure.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|--------|--------|--------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 26.39 | 14.69 | 164.17 | 90.29 | 301.64 | 163.74 |
| C2 | 148.35 | 67.3 | 373.67 | 163.44 | 431.48 | 185.25 |
| C3 | -17.23 | -7.97 | -32.29 | -14.43 | -22.16 | -9.71 |
| C4 | -2.68 | -1.69 | 12.36 | 7.72 | 19.67 | 12.23 |
| C5 | -2.68 | -1.69 | 12.36 | 7.72 | 19.67 | 12.23 |
| C6 | -2.68 | -1.69 | 12.36 | 7.72 | 19.23 | 11.96 |
| C7 | -2.68 | -1.69 | 9.71 | 6.07 | 18.8 | 11.69 |
| C8 | -6.26 | -3.94 | 6.18 | 3.86 | 14.86 | 9.24 |
| C9 | -0.63 | -1.69 | 2.35 | 6.07 | 4.18 | 10.6 |
| C10 | 0 | 0 | 4.77 | 3.57 | 4.73 | 3.52 |
| C11 | -6.74 | -4.38 | -44.62 | -28.86 | -65.78 | -42.38 |

Table 6. Intake air manifold leakage.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|--------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | -80.53 | -45.61 | -130.09 | -74.54 | -184.16 | -107.59 |
| C2 | 5.46 | 2.56 | 12.15 | 5.76 | 24.5 | 11.83 |
| C3 | 181.45 | 84.16 | 356.52 | 162.84 | 743.67 | 328.04 |
| C4 | 47.03 | 29.49 | 90.73 | 56.59 | 185 | 114.07 |
| C5 | 46.58 | 29.2 | 90.73 | 56.58 | 185 | 114.06 |
| C6 | 46.58 | 29.2 | 90.73 | 56.58 | 184.54 | 113.78 |
| C7 | 46.58 | 29.21 | 94.37 | 58.82 | 188.19 | 116 |
| C8 | 43.43 | 27.24 | 90.76 | 56.59 | 184.12 | 113.54 |
| C9 | 43.21 | 29.21 | 90.41 | 63.29 | 183.52 | 115.73 |
| C10 | -15.39 | -11.63 | -32.58 | -24.53 | -62.63 | -48.83 |
| C11 | -37.38 | -24.38 | -90.28 | -58.97 | -65.78 | -42.38 |

Table 7. Cylinder 1 failure.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|---------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 58.84 | 32.86 | 97.66 | 54.47 | 128.93 | 71.85 |
| C2 | -0.69 | -0.32 | -0.69 | -0.32 | -1.38 | -0.64 |
| C3 | -2.51 | -1.18 | -4.39 | -2.07 | -4.39 | -2.07 |
| C4 | 184.31 | 113.14 | 294.48 | 178.01 | 411.86 | 245.07 |
| C5 | 0.45 | 0.28 | 2.67 | 1.68 | 0.44 | 0.28 |
| C6 | 4.91 | 3.1 | 4.45 | 2.8 | 2.22 | 1.4 |
| C7 | 4.46 | 2.81 | 4 | 2.52 | 6.21 | 3.91 |
| C8 | 5.36 | 3.38 | 11.13 | 7.01 | 15.09 | 9.5 |
| C9 | 6.13 | 16.61 | 9.83 | 26.63 | 12.17 | 32.98 |
| C10 | -96.58 | -73.55 | -142.67 | -108.82 | -189.41 | -144.67 |
| C11 | 0.96 | 0.63 | -1.9 | -1.25 | -1.89 | -1.24 |

Table 8. Exhaust manifold leakage.

| | Minor | | Moderate | | Severe | |
|-----|--------|---------|----------|---------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | -203.3 | -137.62 | -352.1 | -237.99 | -660.18 | -448.46 |
| C2 | 8.58 | 4.81 | 17.19 | 9.61 | 35.4 | 19.84 |
| C3 | 2.07 | 1.18 | -2.08 | -1.18 | 4.14 | 2.36 |
| C4 | 66.06 | 39.44 | 130.7 | 77.48 | 258.11 | 151.11 |
| C5 | 66.05 | 39.44 | 130.26 | 77.22 | 258.11 | 151.1 |
| C6 | 66.05 | 39.44 | 131.16 | 77.73 | 258.11 | 151.1 |
| C7 | 66.06 | 39.45 | 128.05 | 75.91 | 275.49 | 161.3 |
| C8 | 63.04 | 37.64 | 124.98 | 74.11 | 258.93 | 151.64 |
| C9 | 13.08 | 39.45 | 25.06 | 75.91 | 49.21 | 151.64 |
| C10 | 176.73 | 157.35 | 365.42 | 311.45 | 748.79 | 597.89 |
| C11 | -58.19 | -44.49 | -135.75 | -100.95 | -266.33 | -187.88 |

Table 9. Turbine failure.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|--------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | -93.79 | -52.58 | -168.06 | -90.64 | -230.84 | -180.25 |
| C2 | -22.7 | -10.58 | -35.63 | -16.65 | -56.71 | -24.58 |
| C3 | -0.62 | -0.3 | -7.44 | -3.54 | -15.14 | -8.25 |
| C4 | 9.36 | 5.92 | 137.77 | 96.57 | 231.25 | 151.54 |
| C5 | 8.91 | 5.64 | 137.33 | 96.29 | 230.54 | 150.24 |
| C6 | 8.91 | 5.64 | 137.33 | 96.29 | 233.17 | 150.29 |
| C7 | 8.91 | 5.64 | 136.44 | 93.74 | 229.57 | 149.75 |
| C8 | 8.91 | 5.64 | 136.44 | 95.74 | 226.93 | 148.91 |
| C9 | 2.02 | 5.64 | 12.21 | 95.74 | 226.71 | 151.86 |
| C10 | 6.71 | 5.11 | -15.95 | -9.4 | -37.48 | -16.24 |
| C11 | 177.64 | 95.43 | 398.72 | 259.78 | 623.78 | 390.71 |

It can be seen from Tables 4–9 that when there are component performance degradation or failures in the diesel engine system, the fuel impact cost ΔF and malfunction of all components will change. The reason for this phenomenon is that during the operation of the diesel engine system, the performance degradation or failure of one component will propagate to the entire system. This phenomenon explains the propagation of faults in the system, which will change the thermodynamic variables involved in the operation of normal components, and then change the operation state of normal components.

The analysis of the malfunction is more important, because the malfunction is caused by the change of the component efficiency. Take the compressor failure in Table 4 as an example, the compressor efficiency will be reduced when scaling and blocking occur inside the compressor. The reduced efficiency of the compressor leads to changes in the efficiency of other components (such as cylinder efficiency). In the absence of any “true failures” (such as scaling, air leakage, blockage) in these other components, the change in efficiency induced by (complex production interactions within the system) is defined as “induced malfunction”. The true source of failure that causes these induced failures is defined as “intrinsic malfunction”. For marine diesel engine systems, the component fault MF analyzed by malfunction and dysfunction theory is usually the superposition of “induced malfunction” and “intrinsic malfunction”.

It can be found in Tables 4–9 that the intrinsic malfunction of the failed component is the largest numerically, which is greater than the induced malfunction in the normal component. However, in some cases, the value of induced malfunction is very close to the intrinsic malfunction, as shown in Table 5. Considering this situation, the fault diagnosis result can only give a set of fault areas.

In addition, in Tables 5,6 and 8, it is found that the components affected greatly are usually adjacent to the fault source as found by Valero’s work. These results can be used to narrow the search range of induced malfunction. Under the conditions of compressor failure and turbine failure, cylinders 1–6 have been greatly affected due to their internal complex chemical reactions, resulting in higher induced malfunction.

In a system with a high degree of coupling between components such as a diesel engine, The propagation phenomenon of component performance degradation or failure is very obvious. Therefore, the malfunction of each component is a superposition of intrinsic malfunction and induced malfunction. Under the assumptions in this section, the fault or performance degradation can be located in the area with a malfunction value.

3.2. Diagnosis results under double fault conditions

Due to the complicated structure of the marine diesel engine system, the possibility of multiple failures occurring at the same time will exist during the working process of the marine diesel engine. In this case, fault diagnosis will be more difficult. Through the permutation and combination of 6 types of failures, 15 types of double failure cases can be obtained. This article lists four representative cases for analysis.

Table 10. Cylinder 1 and Air compressor both failure.

| | Minor | | Moderate | | Severe | |
|-----|---------|--------|----------|---------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 248.3 | 136.64 | 566.61 | 305.55 | 913.69 | 481.8 |
| C2 | 101.49 | 45.76 | 343.51 | 147.91 | 380.51 | 159.72 |
| C3 | -10.91 | -5.01 | -104.46 | -46.49 | -23.3 | -9.99 |
| C4 | 249.85 | 152.38 | 483.6 | 286.15 | 730.91 | 418.43 |
| C5 | 81.27 | 50.79 | 164.89 | 102 | 249.12 | 125.21 |
| C6 | 81.72 | 51.07 | 166.27 | 102.81 | 250.53 | 153 |
| C7 | 84.88 | 53.02 | 169.43 | 104.73 | 250.95 | 153.25 |
| C8 | 84.87 | 53.02 | 172.12 | 106.36 | 249.63 | 152.45 |
| C9 | 23.72 | 65.79 | 45.81 | 130.04 | 63.89 | 184.33 |
| C10 | -112.92 | -85.48 | -209.04 | -157.71 | -309.51 | -232.47 |
| C11 | -77.26 | -50.68 | -178.92 | -118.1 | -264.16 | -175.09 |

Table 11. Cylinder 1 and Air cooler both failure.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|--------|---------|--------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 85.34 | 47.51 | 263.88 | 144.96 | 357.46 | 195.52 |
| C2 | 147.52 | 66.94 | 370.01 | 161.71 | 503.12 | 216.02 |
| C3 | -18.49 | -8.56 | -36.22 | -16.19 | -28.15 | -12.34 |
| C4 | 174.65 | 106.95 | 291.03 | 174.58 | 397.77 | 233.97 |
| C5 | -8.43 | -5.3 | 10.92 | 6.83 | 10.34 | 6.44 |
| C6 | -7.55 | -4.75 | 16.62 | 10.38 | 15.1 | 9.39 |
| C7 | -4.44 | -2.79 | 12.24 | 7.65 | 17.69 | 11 |
| C8 | -3.55 | -2.23 | 16.18 | 10.11 | 25.49 | 15.83 |
| C9 | 4.51 | 12.01 | 10.96 | 28.41 | 14.87 | 37.84 |
| C10 | -77.23 | -58.56 | -128.57 | -96.88 | -177.72 | -133.4 |
| C11 | -6.67 | -4.36 | -45.79 | -29.8 | -68.97 | -44.82 |

Table 12. Air compressor and Air cooler both failure.

| | Minor | | Moderate | | Severe | |
|-----|--------|--------|----------|--------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 207.26 | 113.87 | 567.88 | 302.87 | 822.59 | 412.1 |
| C2 | 256.01 | 113.29 | 596.82 | 247.87 | 819.69 | 314.39 |
| C3 | -28.7 | -12.97 | -47.66 | -20.27 | -40.86 | -16.03 |
| C4 | 74.28 | 46.32 | 131.08 | 80.53 | 528 | 301.72 |
| C5 | 74.29 | 46.31 | 131.08 | 80.53 | 527.99 | 301.69 |
| C6 | 74.28 | 46.31 | 130.64 | 80.25 | 528.5 | 301.93 |
| C7 | 73.84 | 46.05 | 129.75 | 79.74 | 524.3 | 299.7 |
| C8 | 70.7 | 44.11 | 125.77 | 77.32 | 522.99 | 299.07 |
| C9 | 16.82 | 45.77 | 29.97 | 79.74 | 123.59 | 301.07 |
| C10 | -20.06 | -15.08 | -38.47 | -28.5 | -8.55 | -5.86 |
| C11 | -84.37 | -54.96 | -186.27 | -120.8 | -296.51 | -179.92 |

From Tables 10–12, it can be found that the failed component still has a larger MF value. Although in this case, the MF of component is a superposition of intrinsic malfunction and induced malfunction. In addition, due to the superposition of induced malfunction, the MF values of some normal components are also relatively large.

Table 13. Air compressor failure and Intake air manifold leakage.

| | Minor | | Moderate | | Severe | |
|-----|---------|--------|----------|---------|---------|---------|
| | F_i | MF_i | F_i | MF_i | F_i | MF_i |
| C1 | 156.28 | 86.84 | 373.53 | 205.18 | 258.49 | 135.45 |
| C2 | 111.17 | 50.56 | 422.93 | 183.84 | 458.12 | 189.39 |
| C3 | 174.12 | 78.4 | 227.53 | 97.33 | 829.19 | 313.89 |
| C4 | 131.97 | 81.91 | 268.37 | 163.53 | 1097.89 | 590.3 |
| C5 | 131.53 | 81.63 | 268.8 | 163.79 | 1098.35 | 590.51 |
| C6 | 131.52 | 81.63 | 268.35 | 163.52 | 1097.86 | 590.25 |
| C7 | 135.17 | 83.86 | 271.6 | 165.43 | 1086.28 | 584.9 |
| C8 | 131.55 | 81.65 | 268.41 | 163.55 | 1081.41 | 582.5 |
| C9 | 29.9 | 83.59 | 57.5 | 165.7 | 221.03 | 584.9 |
| C10 | −46.74 | −35.1 | −87.37 | −64.76 | −79.53 | −51.99 |
| C11 | −137.51 | −89.96 | −279.03 | −182.68 | −432.08 | −253.73 |

In addition, it can be found in Table 13 when the compressor and the intake air manifold fail at the same time, the coupling effect between the failures will cause a larger induced malfunction in the cylinders, leading to a wrong diagnosis result. Such problems existed in 5 cases, and the components which do not have failures are subject to greater induced effects. Therefore, when multiple faults occur at the same time, the thermoeconomic diagnosis method can only narrow the search range of the fault.

In a system with a high degree of coupling between components such as a diesel engine, therefore, the malfunction MF_i of each component obtained through the malfunction and dysfunction is the superposition of the intrinsic malfunction and the induced malfunction. The interaction among components is a major obstacle in locating the sources of system malfunctions. In another word, we can get more accurate fault diagnosis results by separating the induced malfunction.

However, from a mathematical point of view, it is almost impossible to use the existing methods of thermoeconomics to isolate induced malfunction. Because a lot of information related to system performance has been lost gradually in the process of the establishment of thermoeconomic model, So the author thinks it is necessary to use other modeling methods to supplement the information that has been lost.

4. Conclusions

In the present work, a 6S50-MC engine model was built with AVL BOOST software which can reproduce engine behavior not only under normal conditions but also under failure conditions. Based on the engine model, the application of thermoeconomics in the field of diesel engine fault diagnosis is studied.

The following conclusions can be made:

(1) The model can reflect the behavior of the diesel engine with a deviation between 2% and 3%. In addition, the model can reproduce engine behavior not only under normal conditions but also under failure conditions.

(2) The thermoeconomic fault diagnosis method can quantify the additional fuel impact cost ΔF caused by the fault, and then quantify the additional economic loss caused by the fault, and provide guidance for the repair cycle of the ship.

(3) In a system with a high degree of coupling between components such as a diesel engine, the component fault MF analyzed by malfunction and dysfunction theory is usually the superposition of “induced malfunction” and “intrinsic malfunction”. the thermoeconomic fault diagnosis method cannot accurately locate the fault, but the results can be used to narrow the search range of abnormal components.

(4) This article shows the propagation of faults in diesel engine systems from the perspective of thermoeconomics, which will change the thermodynamic variables involved in the operation of normal components, and then change the operation state of normal components, resulting in induced malfunction in normal components. In addition, this is also the cause of the induced malfunction. Therefore, the interaction between components is the main obstacle to locating the source of system faults. it is necessary to use other modeling methods to supplement the operational parameters of normal components that have been altered to achieve the separation of induced faults. In another word, we can get more accurate fault diagnosis results by separating the induced malfunction.

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Conflict of interest

The authors declare there is no conflict of interest.

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