Study on Quantitative Model of Equipment Main Part Failure Caused by High Temperature

Xiaobo Su1,2,*, Qi Gao1, Qingchun Wu3 and Yukun Chen2

1Shijiazhuang Campus of Army Engineering University, Shijiazhuang, China
2Shijiazhuang Division of PLAA Infantry College, Shijiazhuang, China
3Equipment Support Team of PLAA Equipment Department Beijing, China

*Corresponding author e-mail: giantsu030700@sina.com

Abstract. Aiming at how to quantitative the influence that equipment failure is affected by high temperature, firstly the paper qualitatively analysed the process that energy transfer in engine and cooling system. Then one energy transfer model is set up which is based on the theory of engine and cooling system working. Finally, according to the energy transfer model and engine working time restriction rule, the ‘time-discrepancy’ model and the ‘time-proportion’ model are put forward. These models can be used in quantifying the influence that equipment’s main part working in high temperature environment.

1. Introduction

It is an issue concerned by engineers and scholars that equipment’ working time is influenced by environment. There are many examples that equipment works wrong because of environment reason. It’s investigated by DOD in 1960 that equipment failure caused by environment is over 50 percent in the whole use time [1][2]. Recently when study on the issue of equipment failure environment factor is often be concerned on by some scholars. Environment factors is combined with reliability theory to predict equipment failure in paper [3] and paper [4]. In paper [5] and paper [6] environment parameters are added to the traditional method to calculate ratio of equipment failure. Some data show equipment material’s character will change and equipment’s mechanical capacity will decline in high temperature for a period of time. When equipment is working in high temperature for a long time the failure will increase heavily. How to quantize the influence of high temperature to equipment’s main part is one important issue on research of equipment failure.

2. Conditions and symbol setting

2.1. Conditions

(1) Only high temperature factor is concerned on environment’s influence to equipment engine and cooling system. Other factors are considered to be perfect.
(2) Equipment engine must halt to lower the temperature when the oil or water temperature is too high. Under this situation the engine is considered to be failure.
(3) The oil and water’s temperature is the same as the circumstance at beginning.
(4) The oil and water’s temperature is the same as the circumstance at beginning.
(5) The energy is divided into 3 parts when the oil burn in the engine. Some energy is turned into mechanical energy for the equipment run. Some energy makes the oil and water’s temperature rising. And the remainder energy is released by the radiator.
(6) The weight of the oil and water remains invariable in a certain time.  
(7) The temperature of environment that equipment work in is certain during the period be examined.

2.2. Symbol setting  
\(m_o\) : Oil consumption in unit time.  
\(q_o\) : The fuel value of the oil in equipment.  
\(E_o\) : The energy resealed by the oil when burn in the engine.  
\(Q_o\) : The quantity of heat resealed by the oil when burn in the engine.  
\(Q_x\) : The quantity of heat absorbed by the coolant.  
\(Q_s\) : The quantity of heat resealed by the radiator.  
\(W\) : Mechanical energy.  
\(P_e\) : Equipment’s rated power.  
\(t\) : Equipment’s working time.  
\(t_0\) : The time of equipment working in one fitting environment from when the temperature is the same as the environment’s to the coolant boiling.  
\(t_e\) : The time of equipment working in one high temperature environment from when the temperature is the same as the environment’s to the coolant boiling.  
\(m_{l}\) : The weight of the coolant.  
\(c_i\) : The specific heat capacity of the coolant.  
\(T\) : The timely temperature of the coolant.  
\(T_{b}\) : The temperature at which the coolant boiling.  
\(T_{0}\) : The mean temperature fit for the engine wording.  
\(T_e\) : The temperature of one high temperature environment.  
\(k_i\) : The coefficient of radiator working.

3. Qualitative analysis of temperature’s influence to engine and cooling system

3.1. Engine and cooling system’s operational principle  
Temperature’s main influence to engine is that the engine will be failure when its temperature is too high. So the emphasis is put on the parts of engine, radiator, water pump and coolant which is nearly correlated with heat. The basic frame of engine and cooling system is made up of engine, radiator water pump and coolant too as figure 1.

![Figure 1. Frame of engine and cooling system](image_url)

As power resource for equipment working, the essence of engine work is turn the dinner power in oil into mechanical energy and heat through burnt. The mechanical energy offers power for equipment and the heat makes engine’s temperature rising. If the engine’s temperature rises to a certain higher degree, some failure such as accessories distortion, cylinder conglutination, oil pipe blowout et. All these failures can cause the engine even the whole equipment to paralysis. The function of cooling system is to decline the temperature of engine which can avoid failures above. The cooling system and
engine is connected by some pipes. In the system water pump drives the coolant circulating between engine and cooling system, which can take the heat away from the engine. And the heat is released to the air. At the same time the temperature of the coolant is rising.

3.2. **Analysis on energy transfer**

The procedure that engine offer power for equipment is inner power in fuel change into mechanical power and heat energy though burnt in engine. All energy makes the equipment working such as equipment running, weapons working, fan running comes from the mechanical power. The energy makes the coolant’s temperature rising comes from heat. According to the first law of thermodynamics the procedure can be described as follow.

\[ E_o = W + Q, \]  

According to condition (5), in 2.1, if the burnt degree of the oil is \( k_0 \) burnt equation as formula (2) can be got.

\[ E_o = k_0 m_q t, \]  
The mechanical power equation is as following.

\[ W = P_f t, \]  

Because energy losing except mechanical and heat is ignored, all the energy amount of heat is the total amount of heat absorbed by coolant and released by radiator. So formula (4) can be got.

\[ Q_r = Q_s + Q_s, \]  

According to the first law of thermodynamics coolant absorbs heat can be described by formula (5).

\[ Q_s = c_m \Delta T, \]  
The premise of radiator releases heat is temperature difference between environment and radiator. The temperature of radiator rising along with heat releasing. The amount of heat released in unit time is changing with temperature changes. The basic rule is the amount of heat released is rising along with magnifying of temperature difference. To simplify the procedure temperature difference between radiator and environment is substituted by one average static temperature difference. The average static temperature difference can be used in calculating the heat amount released by radiator when its temperature rising from \( T \) to \( T_f \). The formula is as following.

\[ Q_r = k_s \left( \frac{T_f + T}{2} - T \right) \cdot t \]  

From formulas (1-6), formula (7) can be got, which is the basic equation of energy transfer in engine and cooling system.

\[ k_s m_q t = P_f t + c_m \Delta T + k_s \left( \frac{T_f + T}{2} - T \right) \cdot t \]  

4. **Quantitative model about engine is influenced by high temperature**

4.1. **Method to calculate engine’s working time**

When the coolant in cooling system is boiling, the engine is considered damage. When equipment work in fitting environment, formula (8) can be got according to formula (7).

\[ k_s m_q t_0 = P_f t_0 + c_m \left( T_f - T_0 \right) + k_s \left( \frac{T_f - T_0}{2} \right) \cdot t_0 \]  
The formula used in calculating the working time equipment can work in fitting environment can be got as formula (9) according to formula (8).
On the other hand, formula (10) can be got which is used in calculating engine’s working time in high temperature environment.

\[
t_v = \frac{c_m(T_f - T_e)}{k_o m_o g_o - P_e - k_s \cdot \frac{T_f - T_o}{2}}
\]

According formulas (9) and (10),

For \( T_e > T_o \) Then \( t_e > t_o \)

The calculate result from formula (9) and formula (10) shows engine’s working time in high temperature is shorter than in fitting temperature environment, which is according with the fact.

4.2. Method to calculate the influence of high temperature factor

In terms of the analysis above, the main influence of high temperature to engine is to shorten engine’s working time. According to this basic rule ‘time-discrepancy method’ and ‘time-proportion method’ can be used in quantifying high temperature’s influence to engine’s working time.

4.2.1. Time-discrepancy method

‘Time-discrepancy method’ is using engine’s working time differ between in fitting environment and in high temperature environment to quantify the high temperature’s influence to engine.

Set ‘\( k_1 \)’ as the amount of high temperature’ influence to engine. ‘\( k_1 \)’.can be got from formula (11).

\[
k_1 = t_e - t_o
\]

From formula (9), formula (10), and formula (11) formula (12) can be got.

\[
k_1 = \frac{c_m(T_f - T_e)}{k_o m_o g_o - P_e - k_s \cdot \frac{T_f - T_o}{2}} - \frac{c_m(T_f - T_o)}{k_o m_o g_o - P_e - k_s \cdot \frac{T_f - T_o}{2}}
\]

In formula (12) the numerical values of \( c_j, m_j, k_o, m_o, q_o, P_e, k_s, T_o \) and \( T_f \) are known. So the result of \( k_1 \) only be decided by the numerical value of temperature. Obviously the numerical value of \( k_1 \) is a negative. This shows engine’s working time shorten in high temperature environment. the absolute value of \( k_1 \) rising as \( T_e \) rising. That is to say there are more influence as the environment’s temperature is higher. This is according with the factor.

4.2.2. Time-proportion method

‘Time-proportion method’ is using engine’s working time ratio between in fitting environment and in high temperature environment to quantify the high temperature’s influence to engine.

Set ‘\( k_2 \)’ as the amount of high temperature’ influence to engine. ‘\( k_2 \)’.can be got from formula (13).

\[
k_2 = \frac{t_e}{t_o}
\]

From formula (9), formula (10) and formula (13), formula (14) can be got.
Formula (15) can be got through changing the form of formula (14).

\[
 k_2 = \frac{\left( T_f - T_e \right) \left( k_o m_o q_o - P_e - k_s \cdot \frac{T_f - T_0}{2} \right)}{\left( T_f - T_0 \right) \left( k_o m_o q_o - P_e - k_s \cdot \frac{T_f - T_0}{2} \right)} \times 100\% \tag{15}
\]

Formula (15) is the Time-proportion model to quantify high temperature’s influence to engine. In formula (15), \( k_o, m_o, q_o, P_e, k_s, T_0 \) and \( T_f \) is known. So the result of \( k_2 \) only be decided by the numerical value of temperature.

For \( T_e > T_0 \) Then \( k_2 < 1 \)

From formula (13) engine’s working time in high temperature can be got through formula (16).

\[
 t_e = k_2 \cdot t_0 \tag{16}
\]

Obviously \( k_2 \) becomes less as \( T_e \) rising. That is to say the engine’s work time becomes short and the temperature have more influence to the engine. This is according with the factor.

5. **Example of model applying**

The main part of some equipment is engine. The temperature fitting the engine to work is 10~30ºC. The equipment will work in two regions. The temperature of one region is 20~40ºC. The temperature of the other region is 30~50ºC. The value of the parameters is shown in table 1.

| Parameter | \( T_f \) | \( m_i \) | \( c_i \) | \( k_o \) | \( q_o \) | \( m_i \) | \( P_i \) | \( k_s \) |
|-----------|----------|----------|---------|------|------|-------|------|------|
| value     | 100ºC    | 100kg    | 4.18kJ/(kg•ºC) | 0.9  | 4.3×10⁴kJ/kg | 38kg/h | 404kw | 228kw/h•ºC |

The step to calculate the influence of high temperature to engine is as following.

Stet 1: Calculate the mean of the fitting temperature, the mean of the first region’s temperature and the mean of the second region’s temperature.

The mean of the fitting temperature is as following.

\[
 T_o = \frac{10^\circ C + 30^\circ C}{2} = 20^\circ C
\]

The mean of the first region’s temperature is as following.

\[
 T_{e1} = \frac{20^\circ C + 40^\circ C}{2} = 30^\circ C
\]

The mean of the second region’s temperature is as following.

\[
 T_{e2} = \frac{30^\circ C + 50^\circ C}{2} = 40^\circ C
\]

Stet 2: Calculating of time-discrepancy
Set the amount of time-discrepancy of the first region is \(k_{11}\) and the amount of time-discrepancy of the second region is \(k_{12}\). Put values in table 1 and values of \(T_0, T_{s1}\), into formula (12). \(k_{11}\) can be got as following.

\[
k_{11} = \frac{c_m(T_f - T_{s1})}{k_o m_o q_0 - P_e - k_s \cdot \frac{T_f - T_{s1}}{2}} - \frac{c_m(T_f - T_0)}{k_o m_o q_0 - P_e - k_s \cdot \frac{T_f - T_0}{2}}
\]

\[
= \frac{4.18 \times 100 \times (100 - 30)}{0.9 \times 38 \times 4.3 \times 10^4 - 404 \times 3600 - 228 \times \frac{100 - 30}{2}} - \frac{4.18 \times 100 \times (100 - 20)}{0.9 \times 38 \times 4.3 \times 10^4 - 404 \times 3600 - 228 \times \frac{100 - 20}{2}} = -1.1636 \approx -1.2
\]

That is to say in the first region temperature range is 20~40ºC, the engine’s working time will shorten 1.2 hours than working in the fitting temperature.

Put values in table 1 and values of \(T_0, T_{s2}\), into formula (12). \(k_{12}\) can be got as following.

\[
k_{12} = \frac{c_m(T_f - T_{s2})}{k_o m_o q_0 - P_e - k_s \cdot \frac{T_f - T_{s2}}{2}} - \frac{c_m(T_f - T_0)}{k_o m_o q_0 - P_e - k_s \cdot \frac{T_f - T_0}{2}}
\]

\[
= \frac{4.18 \times 100 \times (100 - 40)}{0.9 \times 38 \times 4.3 \times 10^4 - 404 \times 3600 - 228 \times \frac{100 - 40}{2}} - \frac{4.18 \times 100 \times (100 - 20)}{0.9 \times 38 \times 4.3 \times 10^4 - 404 \times 3600 - 228 \times \frac{100 - 20}{2}} = -2.0437 \approx -2
\]

That is to say in the second region temperature range is 30~50ºC, the engine’s working time will shorten 2 hours than working in the fitting temperature.

Step 3: Calculating of time-proportion

Set the amount of time-proportion of the first region is \(k_{21}\) and the amount of time-proportion of the second region is \(k_{22}\). Put values in table 1 and values of \(T_0, T_{s1}\), into formula (15). \(k_{21}\) can be got as following.

\[
k_{21} = \frac{(T_f - T_{s1})}{(T_f - T_0)} \left( \frac{k_o m_o q_0 - P_e - k_s \cdot \frac{T_f - T_0}{2}}{k_o m_o q_0 - P_e - k_s \cdot \frac{T_f - T_{s1}}{2}} \right)
\]

\[
= \left( \frac{100 - 30}{100 - 20} \right) \left( \frac{0.9 \times 38 \times 4.3 \times 10^4 - 404 \times 3600 - 228 \times \frac{100 - 20}{2}}{0.9 \times 38 \times 4.3 \times 10^4 - 404 \times 3600 - 228 \times \frac{100 - 30}{2}} \right) \times 100\% = 75.36\%
\]

That is to say in the first region temperature range is 20~40ºC, the engine’s working time is 75 percent of working in the fitting temperature.

Put values in table 1 and values of \(T_0, T_{s2}\), into formula (15). \(k_{22}\) can be got as following.
That is to say in the second region temperature range is $30 \sim 50 ^\circ C$, the engine’s working time is 56.73 percent of working in the fitting temperature.

6. Conclusion
The research on environment influence to equipment is at one phase of qualitative analysis. There is few quantitative research on it. Taking temperature as an example the paper illustrated the process of energy transfer in engine and cooling system and analyzed the relationship between equipment’s working environment and its working time. Based on above, one method to quantitative the high temperature’s influence to engine is put forward, which is one exploration on the research of environment influence to equipment.

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