The Effect of Sealing Ring Gap on Hydrogen Peroxide Electric Pump

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Abstract. Chained decomposition will take place in terms of overheat of high concentration hydrogen peroxide, which will further cause explosion, in the electric pump pressurized liquid propellant rocket engine, which takes hydrogen peroxide of high concentration as oxidizing agent, the design of oxidant pump should consider safety factor for temperature rising of hydrogen peroxide and the influence of pump efficiency on quality control of motor system simultaneously. It’s very important to know the effect of sealing ring gap at the bottom of impeller on temperature rising of bearing chamber and pump efficiency. So, this paper firstly establishes mathematical modal about the effect of sealing ring gap on temperature rising of bearing chamber and pump efficiency loss, to gain influencing curve, and then it analyzes parameters of cooling flow and mechanism of temperature rising, and give reasonable gap values, which take both safety and efficiency into account. Finally, 3D simulation calculation is carried out through pumplinx to verify the accuracy of this influence model.

1. Introduction
In May 2017, “Electron” rocket, developed by American rocket laboratory, was launched in New Zealand [1]. The power of this rocket is “Rutherford” liquid oxygen/kerosene engine, in which pump is driven by motor to realize propellant pressurized transportation; in this way, the cost per launch can be reduced to 5 million dollars[2]. So, it has opened up a new development idea for low-cost rocket. And in china, Liu Yang and others [3-6] have carried out some related analysis and research. On the other hand, high concentration hydrogen peroxide is an ideal low-lost and green propellant[7], which was ever applied in “AR” series[8] and “RD-150” serial engines[9]. Besides, experts such as Lin Ge[10], Wang Guangwei[11], and Park[12] also carried out plenty of researches and tests about hydrogen peroxide thrust chamber and turbine pump. Because of its various merits like non-toxic, high density, easy to store at room temperature, and self-inflammable, hydrogen peroxide is very suitable to be served as modern rocket engine oxidizer [13-14], which may further decrease development and operation Difficulty of rocket. However, hydrogen peroxide is unstable, it will decompose in case of overheat and lead to explosion (limiting temperature is 408K in case of 90% concentration) [15-16]. Therefore, for electric pump pressurized liquid propellant rocket engine, which takes battery as energy, and considers hydrogen peroxide as oxidizer, both safety requirement of hydrogen peroxide, and high efficiency demand of electric pump system should be taken into account simultaneously during pump designing.
In hydrogen peroxide pump, lots of friction work for bearing will be converted into heat when running at great speed; and this heat needs to be brought to outside pump through cooling section consisted by hydrogen peroxide within pump, to realize pump heat flow balance. Sealing ring gap, set at the bottom of impeller (figure 1), can be used to restrict cooling flow of bearing. But over large of the gap may lead to excessive loss of pump efficiency, while, if the gap is too small, insufficient cooling flow will be caused for bearing, which may further trigger the risk of overheat of hydrogen peroxide cooling flow. Hence, the gap value is one of the important design parameters for hydrogen peroxide electric pump.

For this reason, the paper explores the effect of sealing ring gap values on temperature rising of bearing cooling flow and pump efficiency loss, and reveals influence law of the gap for hydrogen peroxide pump performance, to obtain rational value for sealing ring gap.

2. Mechanism analysis

2.1. Structure demonstration

Pump structure is shown as figure 1, radial sealing ring is adopted at both inlet and bottom of impeller to limit leakage, which is also a common design structure; however, there are few research related to sealing ring gap at home and abroad [17]. Angular contact ball bearing is selected and installed at bottom region of impeller, high pressure hydrogen peroxide liquid at outlet of impeller flow into bearing chamber after being throttled by sealing ring gap \(\delta\) (at the bottom of impeller). After bearing cooling (when flowing through bearing ball gap), it flows into low-pressure chamber (in front of chamber) through Return pipeline, to form closed loop.

![Figure 1. Structure diagram of hydrogen peroxide pump.](image)

2.2. Mathematical model

As this structure belongs to multi-disciplinary system, if we want to gain temperature rise of bearing, joint solution needs to be conducted for cooling flow model, impeller axial force balance model and bearing power-heat conversion model etc.

2.2.1. Cooling flow model. Coolant flow of hydrogen peroxide is subject to mass conservation law, the major throttle site in flow channel are sealing ring gap and return pline. And ring gap flow model is built according to ring-slot flow formula [18]

\[
q = \frac{\pi d_3 \delta^3 (P_2 - P_3)}{12 \mu l_1}
\]  

(1)

While, Return pipeline flow model is established based upon equation of pipeline pressure loss [19]

\[
q = d_4^4 (P_3 - P_1) / 8 l_2 k
\]  

(2)

\[
Re > 2000, k = 6.8 \left(\frac{q}{vd_4}\right)^{4/3}
\]  

(3)
Where, q is cooling flow, $\delta$ is sealing ring gap (at the bottom of impeller), $P_1$ indicates pump inlet pressure, $P_2$ means impeller outlet pressure, $P_3$ is pressure of bearing chamber, $d_1$ indicates sealing ring diameter at top of impeller, $d_2$, $d_3$ and $d_4$ indicates impeller diameter, sealing ring (the bottom of impeller) diameter, and Return pipeline diameter respectively, $l_1$ and $l_2$ are separately represent length of sealing ring gap (the bottom of impeller) and Return pipeline, besides, $v$ is kinematic viscosity of hydrogen peroxide, $\nu$ is dynamic viscosity of hydrogen peroxide, and $k$ is correction factor.

2.2.2. One-dimensional steady-state axial force balance model of impeller. According to axial pressure distribution on both sides, axial force balance model of impeller is set up to calculate axial load of bearing.

$$\frac{\pi p_2 (d_1^2-d_3^2)}{4} + \frac{\pi d_3^2 p_3}{4} - \frac{\pi d_2^2 p_4}{4} + F_z + F_0 = 0$$

(5)

Where, $F_z$ is axial load of bearing, and $F_0$ is pre-tightening force.

2.2.3. Bearing power-heat conversion model. As power consumption and heating value are decided by frictional torque of rolling bearing, bearing torque equation can be built with common method[19], and frictional heat of bearing can be calculated accordingly.

$$N = 0.1047Mn$$

(6)

$$M_1 = f_1 F_z d_m$$

(7)

$$M_0 = f_0 (vm)^{2/3} d_m^3 \times 10^7$$

(8)

$f_0$ equals to 6.6 with reference to [19]

$f_1$ equals to 7.37×10^{-4} with reference to [19]

Where, $N$ is frictional heat of bearing, $M$ is total frictional torque of bearing, $M_0$ and $M_1$ indicates lubricating oil torque and external load torque of bearing respectively, while, $d_m$ is average diameter of inner and outer ring, $f_0$ indicates bearing structure and lubrication coefficient, $f_1$ represents bearing load coefficient, and $n$ is rotating speed.

2.2.4. Transfer model. According to energy conservation law, cooling heat flow within cooling channel (at steady state) is balanced with frictional heat-power of bearing.

$$Cq\Delta T - N = 0$$

(9)

Where, $\Delta T$ indicates temperature rising of hydrogen peroxide coolant, $C$ is specific heat of hydrogen peroxide.

2.2.5. Model related to effect of sealing ring gap on pump efficiency loss. This equation example only analyzes the effect of sealing ring gap on pump efficiency loss, which mainly consists of two parts, namely, the influence of gap leakage on pump volume efficiency loss, and frictional efficiency loss caused by bearing load variation.

$$\lambda_1 = \frac{q}{Q}$$

(10)

$$\lambda_2 = \frac{N}{Q} \left( P_2 - P_1 \right)$$

(11)

$$\lambda = \lambda_1 + \lambda_2 - \lambda_1 \lambda_2$$

(12)

Where, $Q$ is total flow at pump outlet, $\lambda$ is total efficiency loss induced by gap, $\lambda_1$ indicates volume efficiency loss, and $\lambda_2$ indicates frictional efficiency loss of bearing.
2.3. Analysis of temperature rising and efficiency loss effect

Numerical solution is carried out for δ within 0.01mm to 0.1mm scale by combining above mentioned mathematical model with pump performance and structure parameter in this example, to gain influence curve of δ on bearing cooling flow q, temperature rising ΔT, bearing load Fz and pump efficiency loss λ.

Table 1. Pump structure and performance parameter

| N (rpm) | Q (kg/s) | P1 (MPa) | P2 (MPa) | P3 (MPa) | d1 (mm) | d2 (mm) | d3 (mm) |
|---------|----------|----------|----------|----------|---------|---------|---------|
| 35000   | 4        | 0.5      | 7        | 5        | 28      | 52      | 28      |

| d4 (mm) | dm (mm) | l1 (mm) | l2 (mm) | V (mm²/s) | M (pa·s) | F0 (N) | T0 (K) |
|---------|---------|---------|---------|-----------|----------|--------|-------|
| 3       | 18      | 12      | 400     | 1.14      | 0.00158  | 100    | 300   |

Figure 2. Influence curve of gap on coolant temperature rising.

Figure 3. Influence curve of gap on cooling flow.

Figure 4. Influence curve of gap on bearing load.

Figure 5. Influence of gap on efficiency loss.

It can be seen from figure 2 that when δ increases from 0.01mm to 0.02mm, temperature rising within cooling channel promptly decreases from 116K to 18K, and keeps at trough zone ΔT≤20K in 0.02 to 0.03mm section, afterwards, it slowly rises to 45K and levels off. Cause of such formation: gap throttling effect is prominent when δ=0.01mm, axial load of bearing is smaller, frictional torque is mainly lubricating oil moment with high rotating speed, but cooling flow is only 2.3g/s (figure 3),
which cannot make valid cooling to bearing, and further lead to temperature rising of oil lies in the peak; when gap $\delta$ increases to the area of 0.02mm to 0.03mm, bearing load has little change in this zone, however, cooling flow increases sharply to over 20g/s, and coolant temperature rising lies in the trough; afterwards, $\delta$ continues to increase, pressure at bearing chamber goes up, which leads to axial load $F_Z$ rises greatly (figure 4), and accelerates bearing frictional heating, so, cooling temperature goes up again till $F_Z$ in steady state, and $\Delta T$ keeps at about 45K.

From figure 5, we may know that gap throttling effect is obvious when $\delta$$\leq$0.025mm, and growing rate of $\lambda$ is slow; when $\delta>$0.025mm, influenced by the increase of bearing load, efficiency loss $\lambda$ rapidly goes up to 0.5 and tends to be stable after $F_Z$ being in steady state.

To sum up, if sealing ring gap is in the range of 0.02 to 0.03mm, coolant temperature rising within bearing can be ensured $<20K$(lower range), meanwhile, power loss influenced by gap is less than 12%. So that’s the reasonable range we get.

3. CFD simulation verification

Is conducted for hydrogen peroxide pump in this example by adopting fluid finite element analysis software pumplinx, to verify the accuracy of numerical analysis result of one-dimensional model.

3.1. Modeling and meshing

In this case, UG is utilized to integrally model centrifugal pump from inlet section to outlet of volute casing, and to simply the bearing portion; besides, binary tree algorithm based cartesian grid is employed to divide impeller, volute casing, inlet, bearing chamber and Return pipeline, and the total meshing quantity is 205,343. For sealing ring gap (research focus) ,pumplinx gap mesh tool is used to make encryption meshing, and quantity of encrypted mesh is 300,000.

![Centrifugal pump meshing.](image)

Unsteady simulation method is adopted in this example, what’s more, standard k-ε turbulent model is selected, the mean residual is less than $10^{-3}$, upwind scheme is utilized for pressure term in control equation, and second order upwind is employed for speed term. For boundary condition, pump inlet is set as total pressure inlet, and volute outlet is set as outlet of a given flow; in heat transfer model, heat flow values for inside and outside bearing slide are offered according to model computing results, the given temperature is 300K at pump inlet, volute outlet is set as outlet of heat flow, and all of other walls are insulated boundary.

3.2. Simulation results and analysis

Simulation computation is done separately for $\delta$=0.01mm,0.02mm,0.03mm,0.05mm ,and 0.07mm, the result of temperature field for bearing chamber and cooling channel is shown in figure 8-12. CFD simulation result (in figure 7) indicates that variation trend of temperature in cooling channel is consistent with numerical results, deviation range between $\Delta T$ simulation data and numerical calculation is within 3.4%-11.3% , verified that one-dimensional calculation is relatively accurate, and can be used to rapidly design sealing ring gap.
4. Conclusion
Influence law of sealing ring gap on coolant temperature rising and efficiency loss is obtained by establishing flow model of cooling channel for hydrogen peroxide electric pump, heat transfer model, and bearing power-heat conversion model, and the rational gap size, which both hydrogen peroxide safety and pump efficiency are taken into account, is confirmed. Accuracy of calculation model is verified through CFD simulation computations. This paper provides a feasible plan for rapidly designing critical gap size of hydrogen peroxide electric pump, and in the future, model parameter can be further optimized through pump test and verification.

References
[1] Rocket Lab's Electron Rocket Reaches Space, Satellite Today, May 29, (2017)
[2] Morring,Frank,Jr., Norris,Guy, Electric rocket.(Rocket Lab), Aviation Week & Space Technology, April 27, (2015)
[3] Yang Liu, Jian-gang Yang, Ben-shuai Fu, Guo-qiang He, Pei-jin LIU,System Design of Electric Pump Feed Liquid Propellant Rocket Engine,7th CSA/IAA Conference, 2017.11
[4] Yang Liu,Yuan-bo He,Jian-gang Yang,Chun-bo Hu, Guo-qiang He, Pei-jin Liu,Xiao-fei Zhu, Concept analysis of electric pump pressurized liquid rocket engine,The thirty-eighth technology exchange meeting of Aerospace propulsion Technology Information Society ,2017.8, 352-358.
[5] Jian-gang Yang,Yang Liu,Yuan-bo He, et al., Quality sensitivity analysis of electric pump pressurized liquid rocket engine feed system [C]. The thirty-eighth technology exchange meeting of Aerospace propulsion Technology Information Society, 2017.8, 352-358.
[6] Yang Liu, Ben-shuai Fu, Jian-gang Yang, Yuan-bo He, Pei-jin Liu, Analysis of electric pump pressurized liquid propellant rocket engine system, The 5th Manned Space Conference, 2018.10

[7] Musker A, Highly stabilized hydrogen peroxide as a rocket propellant, AIAA034619,(2003)

[8] Butler Kathleen N, AR2-3 engine refurbishment and gas generator testing, AIAA992738,(1999)

[9] V. I. Arkhangelsky, History of development of hydrogen peroxide Lpreatnpo energomash, IAC(2005)

[10] G. Lin, Q. Ling, F. Li, A Study of thrust chamber technology using hydrogen peroxide, Journal of Rocket Propulsion, (2005)

[11] W. Wang, H. Chen, W. Chen, Y. Du, Development of a peroxide/kerosene turbopump for afterburning cycle for advanced upper stage engine, Journal of Rocket Propulsion, 4 (2016)

[12] Park, Daejong, Jang, et al. Preliminary Test of Turbopump Using Radial Turbine Driven by Hydrogen Peroxide Gas Generator, AIAA (2013)

[13] J. C. Whitehead, M. D. Dittman, A. G. LeDebuhr. Progress toward Hydrogen peroxide Micropulsion, AIAA, (1999)

[14] M. V. Entura, P. Mullens, The Use of Hydrogen peroxide for Propulsion and power, AIAA, (1999)

[15] D. Sengupta, S. Mazumder, J. V. Cole, et al. Controlling non-catalytic decomposition of high concentration hydrogen peroxide, ADA-426795. Springfield. NTIS.

[16] Z. J. Wu, G. Zhou, Explosion Causation Analysis of High Concentration Hydrogen Peroxide in Unsealed System, Chinese Journal Of Explosives& Propellants, 4 (2006)

[17] B. Gao, Z. Wang, Yang L, et al., Effect of wear-ring clearance on performance and flow characteristics of centrifugal pump, Journal of Drainage and Irrigation Machinery Engineering, (2017)

[18] Aero Jet engines Automatic control Handbook, National Defense Industry Press, 6 (2005)

Wang Zhenhua, Bearing Practical Handbook, Shanghai scientific and technological literature press

[19] Wang Zhenhua, Bearing Practical Handbook, Shanghai scientific and technological literature press, (1996)