OPTIMUM DESIGN FOR LRE CENTRIFUGAL PUMPS

by

Zhu Zuchao, Zhang Guoqian, Sun Jiren
HUMAN TRANSLATION
NAIC-ID(RS)T-0820-94  1 May 1995

MICROFICHE NR: 95000274

OPTIMUM DESIGN FOR LRE CENTRIFUGAL PUMPS

By: Zhu Zuchao, Zhang Guoqian, Sun Jiren

English pages: 10

Source: Journal of Propulsion Technology, Nr. 3, June 1992
(Foreign Opinion Source Unknown); pp. 53-58

Country of origin: China
Translated by: SCITRON
F33657-84-D-0165
Requester: NAIC/TATV/Arnold G. Crowder
Approved for public release; Distribution unlimited,

THIS TRANSLATION IS A RENDITION OF THE ORIGINAL FOREIGN TEXT WITHOUT ANY ANALYTICAL OR EDITORIAL COMMENT STATEMENTS OR THEORIES ADVOCATED OR IMPLIED ARE THOSE OF THE SOURCE AND DO NOT NECESSARILY REFLECT THE POSITION OR OPINION OF THE NATIONAL AIR INTELLIGENCE CENTER.

PREPARED BY:
TRANSLATION SERVICES
NATIONAL AIR INTELLIGENCE CENTER
WPAFB, OHIO
GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.
ABSTRACT

We set up a mathematical model to predict low specific speed LRE centrifugal pump unit performance. Using the model in question, performance predictions were carried out for 10 types of LRE centrifugal pumps. Relative errors between experimental values and predicted values associated with efficiency and lift were all within 4%. Using the model in question, design optimization with efficiency as the target function was carried out on AM-7H and 0 pumps as well as AM-1R pumps and AM-50 pumps. Results clearly show that, with a presupposition of surety systems possessing high vapor corrosion characteristics, the efficiencies of these four types of pumps can be respectively raised 6.5%, 5.22%, 5.2%, and 4.41%.

KEY WORDS: Liquid rocket engine, Centrifugal pump, Optimum design

I. LRE CENTRIFUGAL PUMP OPTIMUM DESIGN

LRE centrifugal pump units should possess good vapor corrosion characteristics, high efficiencies, good stability, and similar special traits. With a presupposition of satisfying vapor corrosion characteristics and operating stability, raising pump unit efficiency is the problem which this article wants to solve. Because of this, the article in question adopts efficiency to act as the target function associated with LRE centrifugal pump unit design optimization, taking vapor corrosion characteristics and stability to act as restraining conditions for purposes of treatments.

* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.
2. Mathematical Models

LRE centrifugal pumps operate with rotational speeds which are much higher than centrifugal pumps for civilian use. Fluid flow speeds associated with vane wheels and the interiors of vortical casings are very great. In this way, hydraulic power losses increase. LRE centrifugal pump dimensions will also be smaller than pumps for civilian use. Their relatively high vapor corrosion characteristics require increasing intake diameters. High rotation speeds and active propellants require relatively large operating clearances. All these things cause the efficiencies of LRE centrifugal pumps—with the same sorts of specific rotational speeds \( n_s \) and flow amounts \( Q \)—to be lower than pumps for civilian use. Because of this, when setting up LRE centrifugal pump efficiency models, it is not possible to completely copy related models associated with pumps for civilian use indiscriminately.

1) Calculations of Various Loss Quantities

The various loss quantities that are considered by this article include vane wheel intake hydraulic flow shock \( \Delta H_{sh} \), vane wheel flow path friction loss \( \Delta H_{fr2} \) as well as diffusion loss \( \Delta H_{fr2} \), vortical casing flow path friction loss \( \Delta H_{sf} \) as well as diffusion loss \( \Delta H_{sx} \), diffuser loss \( \Delta H_{d} \), as well as vane wheel power depletion \( \Delta P_d \), and so on.

\[
\Delta H_{sh} = k_1 \frac{W^2}{2g} \\
\Delta H_{fr1} = k_2 \frac{\lambda l}{D_w} \cdot \frac{W^4}{2g}
\]

(1)

(2)

In the equations, \( l, D_w, E \) and lambda are, respectively, vane wheel flow path hydraulic length, diameter, relative speed and friction coefficient.
\[ \Delta H_{tr} = 0.2(W_1^2 - W_1^3)/g \]  
(3)

\[ \Delta H_u = 0.2k_3 \frac{C_s^2 - V_{th}^4}{2g} \]  
(4)

\[ \Delta H_t = k_4 \dot{\zeta}_{s} \frac{V_{th}^4}{2g} \]  
(5)

In the equations, \( \zeta_s \) is diffuser diffusion coefficients

\[ \zeta_s = \frac{\lambda}{\sin \frac{\gamma}{2}} (1 - \eta^4) + \sin \gamma (1 - \eta^2)^2 \]

\( n \) and \( \gamma \) are, respectively, diffuser area ratios and expansion angles.

\[ \Delta H_u = k_4 \lambda \frac{1}{d} \cdot \frac{V_{th}^4}{2g} \]  
(6)

In equations, \( l \) and \( V_{th} \) as well as \( d \) are vortical casing lengths, vortical casing throat section speeds, and equivalent round tube diameters.

Overall hydraulic power losses \( \Sigma \Delta H \) are:

\[ \Sigma \Delta H = \Delta H_u + \Delta H_{tr} + \Delta H_{fl} + \Delta H_{fr} + \Delta H_k + \Delta H_m \]  
(7)

\[ \Delta P_d = 5.038 \times 10^{-3} k_5 C_s pU_1^2 \frac{D_1^2}{2g} \quad (kW) \]  
(8)

\[ C_s = 0.0465 \left( \frac{U_1 D_1}{2g} \right)^{0.2} \]  
(9)

In the equations above, \( k_i \) \((i=1,2,\ldots,5)\) are correction coefficients related to specific rotation speeds.

\[ k_i + 1 = x_{i+1} + x_{i+1} \cdot n_{i+1} \quad i=0,1,\ldots,4 \]  
(10)

In this, \( x_i \) \((i=1,2,\ldots,15)\) are specific coefficients.
2) Prediction Models

LRE centrifugal pump efficiencies can be expressed as:

\[ \eta = \frac{1}{\eta_v + \frac{\Delta P_v}{N_e} + 0.05} \quad (11) \]

In the equation above, \( \eta_v \) and \( \eta_h \) as well as \( N_e \) are volume efficiencies, hydraulic power efficiencies, and effective powers.

\[ \eta_v = \frac{1}{1.0 + 0.68 n_v^{-\frac{1}{2}}} \quad (12) \]

\[ \eta_h = \frac{H}{H_{th} + H_{in}} \quad (13) \]

LRE centrifugal pump lift prediction models are as follows:

\[ H = H_{ind} + (H_{th} - \Sigma \Delta H) \quad (14) \]

For calculations of induction wheel actual lift \( H_{ind} \) and theoretical lift \( H_{in} \) as well as centrifugal wheel theoretical lift \( H_{th} \), see references [1] and [2].

3) Solution for the Constants \( x_i \) Awaiting Specification

When calculating \( \Delta H_{in}, \Delta H_{ir}, \Delta H_{in}, \Delta H_{in}, \Delta H_{in} \) as well as \( \Delta P_d \) above, we introduced the correction coefficients \( k_i \) (i=1,2...5). Among these are included 15 coefficients awaiting specification \( x_i \) (i=1,2...15). Below, we use direct P-H optimization methods in order to solve for \( x_i \). With a view toward LRE centrifugal pumps, statistical calculations were carried out on their properties. In conjunction with this, taking equation (15) to act as the target function, \( x_i \) was taken to act as the optimization variable, and optimization calculations were carried out, causing calculated efficiencies and actual efficiencies, calculated lifts and actual lifts, to have the most proximate levels.
Minimization

\[ F(X) = \left[ \frac{1}{N} \sum_{i=1}^{N} (\eta_i - \eta_0)^2 \right]^{0.5} + \left[ \frac{1}{N} \sum_{i=1}^{N} \left(1.0 - \frac{H_i}{H_D} \right)^2 \right]^{0.5} \]  

(15)

causes agreement with:

\[ 0.20 \leq k_{i+1} = x_{3i+1} + x_{3i+2} \cdot n_i^{3i+3} \leq 1.5 \quad i = 0, 1 \ldots, 4 \]

Use is made of P-H [3] methods to solve for \( x_i \) as below:

- \( x_{3-8} = 0.7884, -1.5958, -1.0124, 14.1687, -14.2856 \)
- \( x_{9-16} = 0.004796, 3.0631, -2.7985, 0.005481, 1.0341 \)
- \( x_{17-15} = -0.6642, -4.1812, 0.7637, 0.006831, 0.5855 \)

These 15 constants connect equation (1) ... equation (14) and together form mathematical models for LRE centrifugal pump unit characteristic predictions.

4) Characteristic Prediction Cases

Using the models in question, performance predictions were carried out on 10 types of LRE centrifugal pumps. From Table 1, one learns that there is good agreement between predicted values and actual values associated with design operating status points. Maximum relative efficiency error is 3.87%. Besides the relative lift error associated with AM-2R pumps being 4.90%, the rest are all within 4%. It is possible to see that prediction precision is very satisfactory.

3. Design variables

Design variables adopted by this article include induction wheel intake flow amount coefficients \( \Psi_{\text{ind}} \), intake diameter ratios \( R_d \), and intake flow fluid angles of attack \( \alpha_{\text{ind}} \).
TABLE 1. LRE CENTRIFUGAL PUMP UNIT PERFORMANCE PREDICTION VALUES AND EXPERIMENTAL VALUES

<table>
<thead>
<tr>
<th>1</th>
<th>型</th>
<th>AM-7</th>
<th>AM-2</th>
<th>AM-3</th>
<th>AM-4</th>
<th>AM-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>枚别</td>
<td>H</td>
<td>O</td>
<td>Y</td>
<td>R</td>
<td>Y</td>
</tr>
<tr>
<td>η′</td>
<td>%</td>
<td>56.5</td>
<td>68.0</td>
<td>72.1</td>
<td>67.4</td>
<td>73.1</td>
</tr>
<tr>
<td>η</td>
<td>%</td>
<td>55.0</td>
<td>70.3</td>
<td>75.0</td>
<td>68.0</td>
<td>74.0</td>
</tr>
<tr>
<td>ση</td>
<td>%</td>
<td>2.72</td>
<td>3.3</td>
<td>3.87</td>
<td>0.88</td>
<td>1.21</td>
</tr>
<tr>
<td>H</td>
<td>m</td>
<td>6276</td>
<td>383</td>
<td>723</td>
<td>1568</td>
<td>954</td>
</tr>
<tr>
<td>H0</td>
<td>m</td>
<td>6289</td>
<td>398.8</td>
<td>721</td>
<td>1495</td>
<td>960</td>
</tr>
<tr>
<td>Hs</td>
<td>m</td>
<td>6369</td>
<td>396</td>
<td>740</td>
<td>1517</td>
<td>989</td>
</tr>
<tr>
<td>σH</td>
<td>%</td>
<td>0.21</td>
<td>3.96</td>
<td>0.28</td>
<td>4.90</td>
<td>0.63</td>
</tr>
<tr>
<td>σH0</td>
<td>%</td>
<td>1.77</td>
<td>3.3</td>
<td>2.3</td>
<td>2.36</td>
<td>3.54</td>
</tr>
</tbody>
</table>

Key: (1) Model (2) Pump Specification

Note: \(\sigma_\eta = \frac{\eta' - \eta}{\eta}, \sigma_{H0} = \frac{|H' - H0|}{H0}, \sigma_{Hs} = \frac{|H' - Hs|}{Hs}\)

Items carrying a' are prediction values from this article. \(H_c\) and \(H_s\) are design and experimental lifts.

\(\alpha_{ind}\) installation angles \(\beta_1\) and \(\beta_2\) of intake and exhaust blades associated with centrifugal wheels, intake and exhaust diameters \(D_1\) and \(D_2\), intake and exhaust widths \(b_1\) and \(b_2\), blade numbers \(Z\), as well as vortical casing throat areas \(F\). That is:

\[X = (\psi_{ind}, R_d, \alpha_{ind}, D_1, D_1, b_1, b_2, \beta_1, \beta_2, F, Z)^T\]
4. Restraining Conditions

1) Restraining Conditions Determined by Design Requirements

LRE centrifugal pump unit induction wheel vapor corrosion specific rotation speeds $C_{kp1}$ should be larger than pump unit critical vapor corrosion specific rotation speeds $C_{kp1}$ or larger than vapor corrosion specific rotation speeds $C_{onst}$ associated with design requirements, that is:

$$C_{kp1} - 1.36 \cdot C_{kp1} \geq 0$$
$$C_{kp1} - C_{onst} \geq 0$$

(16) \hspace{1cm} (17)

Besides this, in order to guarantee the lack of vapor corrosion fractures in operating states, induction wheel lift $H_{ind}$ should be accurately specified according to the equation below:

$$0.08 \leq \frac{H_{ind} + NPSH_i - NPSH_i}{U_d^2 \cdot g} \leq 0.15$$

(18)

In equations, $NPSH_i$ and $NPSH_r$ as well as $U_d$ are circular velocities associated with diameter location induction wheel gas corrosion margins, centrifugal wheel intake dynamic pressure drops, and induction wheel calculations.

(2) Lifts $H$ produced by pump units should be larger than design lifts $H_D$, that is:

$$H_{ind} + (H_{in} - \sum \Delta H) - (1.01 \sim 1.03) \cdot H_D \geq 0$$

(20)

(3) Centrifugal wheels must not give rise to the appearance of flow disengagement and loss of speed, that is:

$$0.8 \leq \frac{W_1}{W_2} \leq 1.4$$

(21)
2) Selection Ranges for Design Variable Values and Additional Restraints

Their precise specification will be explained in concrete examples.

5. Optimum Design Cases and Analyses

Below we take the AM-1R pump as an example and carry out LRE centrifugal pump unit optimum design. The design parameters are as follows:

Flow Amount \( Q = 0.0394 \text{m}^3/\text{s} \)
Design Lift \( H_d = 1030 \text{m} \)
Revolution Speed \( n = 16500 \text{r/min} \)
Specific Revolution Speed \( n_s = 65.3 \)

On the basis of AM-1R pump original structural dimensions, we give design variable ranges and additional restraints as below:

\[
egin{align*}
0.065 \leq & \psi_{iad} \leq 0.135 \\
0.16 \leq & R_d \leq 0.25 \\
0.3 \leq & \frac{D_1 - D_i}{4D_1b_1} \leq 1.0 \\
16^\circ \leq & \beta_1 \leq 25^\circ \\
0.6b_1 \leq & b_2 \leq 1.4b_1 \\
\beta_1 - \beta_i \geq & 0 \\
8^\circ \leq & a_{imp} \leq 16^\circ \\
3.0^\circ \leq & a_{iad} \leq 7.0^\circ \\
0.6D_1 \leq & D_2 \leq 1.4D_1 \\
0.65 \leq & \frac{D_1}{D_i} \leq 0.95 \\
18^\circ \leq & \beta_2 \leq 60^\circ \\
0.7F' \leq & F \leq 1.3F' \\
6^\circ \leq & \beta_{iad} \leq 15^\circ \\
\Delta \beta_i \geq & 0
\end{align*}
\]

On the basis of actual states of LRE centrifugal pumps, we get empirical formulae for the calculation of \( D_2 \), \( b_2 \), and \( a_{iad} \) as follows:


\[ D_i = 19.2 \left( \frac{n_1}{100} \right)^{1/6} \cdot \sqrt{\frac{2gH_0}{n}} \]

\[ b_i = 2.413 \left( \frac{n_1}{100} \right)^{0.8744} \cdot \sqrt{\frac{2gH_0}{n}} \]

\[ F' = \frac{Q}{(0.661 - 0.00235n_1) \sqrt{2gH_0}} \]

In situations with a centrifugal wheel blade number \( Z = 7 \), the results and original parameters are shown in Table 2. From Table 2, one learns that, with a presupposition of surety system vapor corrosion performance, efficiencies are raised from the original 64.3% to 69.5%, that is, an increase of 5.2%.

**TABLE 2. COMPARATIVE PARAMETER TABLE FOR AM-1R PUMPS BEFORE AND AFTER OPTIMIZATION**

<table>
<thead>
<tr>
<th></th>
<th>( D_i ) (mm)</th>
<th>( \psi_{1+e} )</th>
<th>( R_k )</th>
<th>( a_{1+e} )</th>
<th>( \beta_{1+e} )</th>
<th>( b_1 )</th>
<th>( b_2 )</th>
<th>( D_1 )</th>
<th>( D_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>实际值</td>
<td>84</td>
<td>0.1081</td>
<td>0.238</td>
<td>4.98</td>
<td>11.15</td>
<td>32</td>
<td>15</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>优化值</td>
<td>79.24</td>
<td>0.1282</td>
<td>0.226</td>
<td>6.4</td>
<td>14.36</td>
<td>26</td>
<td>14.7</td>
<td>74.4</td>
</tr>
<tr>
<td>1</td>
<td>名称</td>
<td>( \beta_1 )</td>
<td>( \beta_2 )</td>
<td>( a_{1+e} )</td>
<td>( F )</td>
<td>( \Delta H )</td>
<td>C_s</td>
<td>( W/W_s )</td>
<td>( H(m) )</td>
</tr>
<tr>
<td>3</td>
<td>实际值</td>
<td>20</td>
<td>24.07</td>
<td>7.51</td>
<td>6.24</td>
<td>229</td>
<td>4404</td>
<td>1.31</td>
<td>1030</td>
</tr>
<tr>
<td>3</td>
<td>优化值</td>
<td>16.8</td>
<td>37.51</td>
<td>7.75</td>
<td>6.84</td>
<td>168.7</td>
<td>4172</td>
<td>1.218</td>
<td>1048.5</td>
</tr>
</tbody>
</table>

Key: (1) Nomenclature (2) Actual Value (3) Optimization Value

Besides this, optimum designs were also carried out for AM-70 and H pumps as well as AM-50 pumps. The design parameters are shown below. From the table below, one knows that efficiencies associated with these three types of pumps after optimization are capable of, respectively, increasing 5.22%, 5.9%, and 4.41%.

<table>
<thead>
<tr>
<th></th>
<th>( Q ) (m(^3)/s)</th>
<th>( H_o )</th>
<th>( n ) (r/min)</th>
<th>( \eta_s )</th>
<th>( \eta_2 ) 实际效率</th>
<th>( \eta_3 ) 优化后效率</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM-70</td>
<td>0.00806</td>
<td>398.85</td>
<td>18480</td>
<td>68</td>
<td>70.3%</td>
<td>75.52%</td>
</tr>
<tr>
<td>AM-71</td>
<td>0.02592</td>
<td>594.9</td>
<td>36960</td>
<td>32.06</td>
<td>55.6%</td>
<td>61.54%</td>
</tr>
<tr>
<td>AM-50</td>
<td>0.01383</td>
<td>558.3</td>
<td>20000</td>
<td>74.74</td>
<td>66%</td>
<td>70.44%</td>
</tr>
</tbody>
</table>

Key: (1) Centrifugal Pump Nomenclature (2) Actual Efficiency (3) Efficiency After Optimization (4) Pump
II. CONCLUSIONS

1. This article set up mathematical models for predicting LRE centrifugal pump performance. Using the models in question, predictions were carried out for 10 types of LRE centrifugal pumps. The results clearly showed that the relative errors between predicted values and actual values associated with efficiencies and lifts were all within 4%.

2. This article set up optimum design methods for LRE centrifugal pump units. Optimization was carried out on AM-1R pumps, AM-70 pumps, II pumps, and AM-50 pumps. The results clearly showed that, with a presupposition guaranteeing that pump units possess high vapor corrosion performance, the efficiencies can respectively go up 5.2%, 5.22%, 6.5%, and 4.41%.

3. This article gives performance prediction and optimum design programs with strong general utility, fast computation speeds, and high precision. They are capable of use in the test manufacture of current and future LRE centrifugal pumps and CAD advances. In the design of centrifugal pumps for civilian use, they also have very great significance.

REFERENCES

[4] 张国乾.泵机组设计探讨. 航天部11所
### DISTRIBUTION LIST

---

**DISTRIBUTION DIRECT TO RECIPIENT**

---

<table>
<thead>
<tr>
<th>ORGANIZATION</th>
<th>MICROFICHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>B085 DIA/KTS-2FT</td>
<td>1</td>
</tr>
<tr>
<td>C509 BALLOON BALLISTIC RES LAB</td>
<td>1</td>
</tr>
<tr>
<td>C510 R&amp;T LABS/AVEADCOM</td>
<td>1</td>
</tr>
<tr>
<td>C513 ARRAOCOM</td>
<td>1</td>
</tr>
<tr>
<td>C535 ARRAOCOM/TSARCOM</td>
<td>1</td>
</tr>
<tr>
<td>C539 TRASANA</td>
<td>1</td>
</tr>
<tr>
<td>Q592 FSTC</td>
<td>4</td>
</tr>
<tr>
<td>Q619 MSIC REDSTONE</td>
<td>1</td>
</tr>
<tr>
<td>Q008 NTIC</td>
<td>1</td>
</tr>
<tr>
<td>Q043 AFMIC-IS</td>
<td>1</td>
</tr>
<tr>
<td>E051 HQ USAF/INET</td>
<td>1</td>
</tr>
<tr>
<td>E404 AEDC/DOF</td>
<td>1</td>
</tr>
<tr>
<td>E408 AFWL</td>
<td>1</td>
</tr>
<tr>
<td>E410 AFUTC/IN</td>
<td>1</td>
</tr>
<tr>
<td>E429 SD/IND</td>
<td>1</td>
</tr>
<tr>
<td>P005 DOE/ISA/DDI</td>
<td>1</td>
</tr>
<tr>
<td>P050 CIA/OCR/DDC/SD</td>
<td>2</td>
</tr>
<tr>
<td>1051 AFIT/LDE</td>
<td>1</td>
</tr>
<tr>
<td>P090 NSA/CDB</td>
<td>1</td>
</tr>
<tr>
<td>2206 FSL</td>
<td>1</td>
</tr>
</tbody>
</table>

Microfiche Nbr: FTD95C000274
NAIC-ID(RS)T-0820-94