Modelling of friction and wear for cryogenic valve seals of rocket engines

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ABSTRACT

Based on the experimental results, earlier work presented a first attempt at the statistical modelling of the friction and wear valves and seals of rocket engines must withstand.

Available friction coefficients and wear rates (as defined in Archard's equation) were fitted against two independent variables : sliding speed and contact pressure. The computations yielded second-degree polynomials and the corresponding response surfaces.

However, it was felt that a statistical design of experiments to reduce the test activities and maximise result quality was needed. A detailed analysis led to the choice of Doehlert's approach, with a contribution of the general equiradial design.

Testing was performed with a pin-on-disk tribometer capable of working at room temperature (RT) and under liquid nitrogen (at 77 K).

The results pertaining to two examples are discussed. Statistical as well as practical aspects of the work performed and consequences of the results are covered : based on correlation factors and other mathematical indicators, on the general profile of the response surfaces and on requirements for use, the tribological properties of the considered materials are illustrated, leading to their eventual usefulness in cryotechnic equipment and space applications.

1. INTRODUCTION

The flow of liquid ergols (LH_2 at 20 K and LOX at 90 K) in modern rocket engines is regulated by valves operating under very severe conditions of pressure, sliding speed and environment for large number of cycles. The critical element that limits life is the valve seal or seat.

As discussed in earlier work [Refs. 1 and 2], their design involves an empirical approach, due to a lack of documented design data and imperfectly understood phenomena of valve seating and flow control.

The tribological aspects of sealing raise difficult questions and answering them through modelling is a very helpful and efficient method.

2. TRIBOLOGICAL MODELLING

2.1. General considerations

The method adopted for the case under study is a statistical approach, based on regression analysis [Ref.2]. It approximates the dependent variable (wear rate or coefficient of friction) to a polynomial of the first or second degree in the independent variables (experimental quantities like sliding speed, contact pressure, duration of experiment or material properties like elastic modulus or thermal characteristics). The regression coefficients are usually determined by the method of least squares.

The test results may be presented in two forms : three-dimensional diagrams (response surfaces) and contour forms (projection of the constant-value lines of the response surface on the x-y plane).

The wear rate is defined in Archard's classical equation : $W = k\ L\ D$

where W : is the volume of wear (mm^3) ;
L : is the normal force (N) ;
D : is the distance (m) ;
k : is the wear rate in mm^3/Nm

The coefficient of friction (f, non-dimensional) and the wear (k in 10^{-6} mm^3 /Nm) are thus expressed as second-degree polynomial functions of contact pressure (y in MPa) and sliding speed (x in m/sec) :

$$f = a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5xy \ ;$$
$$k = b_0 + b_1x + b_2y + b_3x^2 + b_4y^2 + b_5xy \ ;$$

Results pertaining to continuous motion were presented and discussed in Ref. 1. Tests under reciprocating motion were performed to complete the set of data and to examine the possibility of linking both types of motion [Ref. 2].

However, data points were obtained within the scope of several development programmes and, while they covered extensive ranges of contact pressures and speeds both at RT and under LN_2, they had not been acquired on a systematic, optimised basis.

Therefore, it was felt that a statistical design of experiments to reduce the test activities and maximise result quality was needed.

2.2 Statistical test planning

A short list of references dedicated to the methods available to draw a test plan is included at the end of this document [Ref 3-6].

To streamline test campaigns and improve their efficiency, a formal test plan must be set up, as follows :

After identifying the most influent factors on the variables of interest, through former knowledge and preliminary screening tests, it is requested to model the variations of the variables as a function of these factors.
When they are quantitative, this step is called surface response modelling. This leads to the main goals of the test campaign : predict and optimise the response.
In the present case, the variables are the friction coefficient and the wear rate. The quantitative factors are the sliding speed and the contact pressure.
As before, the model will be limited to the order 2.

2.3. Testing specifications

The test plan must fulfil the following (not exclusive) requirements :

- Involve enough points in suitable locations to allow an estimate of the terms in the chosen model and validate it ;
- Be sequential with respect to the range ; if this must be moved, it should be done at the lowest cost and without losing the benefit of earlier testing ;
- Yield accurate and independent estimates of the parameters ; orthogonal or quasi-orthogonal properties ;
- Predict as accurately as possible over the whole range :
  - isovariance or absence of « privileged » direction. The precision is just a function of the distance between the prediction and the centre of the range ;
  - uniform precision. The precision is the same everywhere in the range.

The last two properties evaluate the quality of a plan (or design).

2.4. Model of the second order

The general model of order 2 for k **quantitative** factors may be written as :

$$Y = a + \sum_{1}^{k} b_j X_j + \sum_{j=1}^{k} b_{ii} X_i^2 + \sum_{j=1}^{k} \sum_{j=i+1}^{k} b_{ij} X_i X_j + \varepsilon$$

The model takes into account :
- the direction and the amplitude of the main effects of the factors (signs and magnitudes of the b_j) ;
- their shape or curvature (signs and magnitudes of the b_{jj}) ;
- the linear interaction of the factors two by two (magnitudes of the b_{ij}) .

The model does not take into account :
- a change of curvature due to one factor ;
- the influence of one factor over the curvature due to another.

Experience shows that the model of order 2 yields a reasonable approximation of a continuous phenomenon in many cases.

These predictions are often represented by the response surface or by sets of curves projected on a plane (levels).

Many plans are discussed in the literature for the treatment of models of order 2. After a careful examination, it was decided to adopt Doehlert's approach.

Doehlert's or « uniform shell design » is a plan adapted to the adjustment of a second order model for quantitative factors.
It is economical and specially suited for prediction and optimisation. It involves a sequential approach with respect to factors and experimental range.
But it does not possess « a priori » the properties of orthogonality and isovariance.
Such a plan consists in $N = k^2 + k + n_0$ tests ; $k^2 + k$ tests are arranged on a sphere of radius 1 and n_0 tests are located at the centre of the range.
It may be seen that the number of levels treated per factor varies.The levels are symmetrically distributed around the origin but not uniformly distributed in each interval(-1,+1).

Further theoretical considerations indicate approaches and yield formulas that :

- show how to locate points on concentric circles (spheres) ;
- how to compute the radii of these circles (spheres) ;
- ascertain how either « orthogonality » or « uniform accuracy » can be pursued with the improvements of the general equiradial design.

2.5. Construction of the test plan

Considering the number of tests to be performed during the campaign and the inherent inaccuracy of tribological data, it was decided to choose the « orthogonality » approach ; in other words, to make the effect of one factor as independent as possible from the effect of the other, rather than to look for best accuracy over the experimental range.
This leads us to choose 3 concentric circles :
- a circle with radius = 0 ($r_0 = 0$) ;
- a circle with unit radius ($r_1 = 1$) ;
- a circle with radius ($r_2 = 0.328 < 1$)

The experimental points are located as follows :

- at $r_0 = 0$: 2 points ;
- at $r_1 = 1$: 6 points (original hexagon of Doehlert) ;
- at $r_2 = 0.328$: 7 points (contribution from general equiradial design) yielding a total of 15 points per test plan.

For a display of these points, see Figure 1.

Applying Doehlert's approach to the case under study, we must derive :

- a second order equation (model) ;
- the coordinates of the test points ;

The values for the sliding speed range from 0.05 to 0.20 m/s (alternating motion) ; those for the contact pressure range from 5 MPa to 25 MPa.
Doehlert's plan yields the following coordinates, plotted in Fig. 1 :

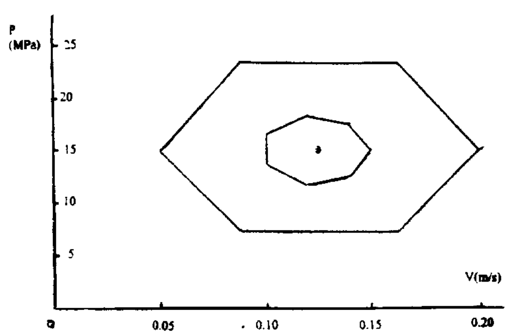

Figure 1 – Plot of experimental values

3. TESTING CONDITIONS

3.1. Cryotribometer

To evaluate the tribological behaviour of polymers sliding on metals an automated ISMCM-CNES pin-on-disk tribometer capable of operating under LN2 has been installed at the University of Liege. This equipment is already referred to and illustrated in Ref. 1. It has been modified to perform reciprocating motion with a maximum speed of 0.2 m/s.

3.2. Tribological pairs

Two tribological pairs are presented ; the polymer pins were made of :
- PCTFE (polychlorotrifluoroethylene) ;
- a polyimide filled with 15 % MoS_2.

The first pair rubbed against disks machined from aluminium alloy 2024 and then anodised ($R_a = 0.20$ µm).

The second pair disks were machined from forged bars of austenitic stainless steel A286 (with $R_a = 0.15$ µm and HB between 277 and 363).

3.3. Testing conditions

Details about testing conditions may be found in Ref. 2. Summarising those applied during the campaigns under study :
- Testing was performed at RT and 77K;
- Experiments were carried out under reciprocating motion with a stroke of 0.09 m and a 2 sec dwell time between reversals to simulate actual conditions in the valves ;
- As already mentioned in § 2.5., the sliding speed varied between 0.05 and 0.20 m/s ;
- The contact pressure ranged between 6.34 and 23.66 MPa ;
- Considering that for flat-on-flat conditions a maximum load of 750 N is allowed, the cylindrical pins had diameters of either 8 or 6 mm depending on the required stress level ;
- The number of cycles was fixed at 1500.

4.TEST RESULTS AND DISCUSSION

4.1. General comments

All the coefficients of friction were obtained as continuous recordings and the average value of each test is reported.

For flat pins, the wear rates were obtained from the difference in weight at the beginning and end of a test., wear rates were computed with the usual Archard's formula .

Applying the method of § 2 for each tribological pair, computations were performed at 2 temperatures for the friction coefficient and the wear rate, respectively. Therefore, four equations together with their response surfaces were obtained per pair.

Every equation is illustrated by two graphical representations :

1. A diagram giving for each (P-V) couple the corresponding values of f or k ; this allows to evaluate possible differences between calculated and experimental values ;
2. A response surface on the same scale as the diagram of data points. In this way, superposing the two diagrams emphasizes the fit between data points and response surface.

On the diagrams, experimental data points are represented by small triangles or squares. The computed values lie at the end of the vertical dashed lines.

4.2. Examples

The space available for this presentation does not allow a full discussion of the results pertaining to the pairs quoted in § 3.2. hereabove.
Two examples will now be commented in detail.
General conclusions are to be found in § 4.3.

1. PCTFE/Al 2024 under LN_2 (at 77 K)

The numerical results corresponding to the 15 conditions are presented in table 1, together with the values of pressure and speed, their squares and products.

The statistical analysis yields the coefficients of the second-degree equations for f and k at the bottom of the table and each under its respective variable (constant, p, v, p^2, v^2, pv).

Figure 2a shows the experimental and computed results for the coefficient of friction, figure 2b gives the response surface. Figures 2c and 2d give the same information for the wear rate.

Table 2 presents the pertinent statistical information :

- the top line gives the correlation factors (r^2) and the standard deviation (s) for f and k, respectively ;
- the first and fifth columns give the computed values f_m and k_m respectively ;
- the second and sixth columns give the differences between experimental and computed values of $f-f_m$ and $k-k_m$;
- the third and seventh columns give the ratios of the differences to the experimental values in % : 100 X $(f-f_m)/f$ and 100 X $(k - k_m)/k$;
- the fourth and eighth columns give the ratios of the differences to the standard deviations $(f-f_m)/s$ and $(k - k_m)/s$ or Nf_m and Nk_m.

The values of Nf_m and Nk_m are the most interesting ones, as regards the statistical evaluation of the results. It is considered that values above |2| are indicative of difficulties with the use of the test results.
The general observations made earlier in Ref. 2 are valid in the present case :
- other things being equal, the friction coefficient tends to decrease as the contact pressure increases ; this is a feature generally observed with polymers ;
- the friction coefficient varies around 0.14 at 77 K ; this is quite close to the values obtained with the PCTFE/A286 pair : ≈ 0.15 ;
- the values of k at 77 K are again close to those observed with the A286/PCTFE pair and are acceptable : = 5×10^{-6} mm^3/Nm.

The numerical values reported in table 2 call for some comments, in particular as regards the correlation coefficients (r^2).

The r^2 's seem rather low, indicating a not very good fit between experimental and computed results, at least with a second-degree (quadratic) model.

However, one must keep in mind the inherently large inaccuracy affecting tribological data. As already explained in earlier reports, quoting a friction coefficient ± 10 % and a wear rate within a factor of 4 is usual [Ref 7].

2. Polyimide filled with MoS2/A286 at room temperature

The same procedure was followed and yielded the information summarised in figure 3 (a to d)

Table 1

N°	Experimental values		Independent variables				
	mm^3/Nm (E-6)		MPa	m/s			
	Friction	Wear	P Hertz	V	P^2	V^2	PV
1	0.1	9.93	15	0.05	225	0.0025	0.75
2	0.14	8.95	15	0.2	225	0.04	3
3	0.16	9.93	6.34	0.0875	40.1956	0.00765625	0.55475
4	0.1	6.83	6.34	0.1625	40.1956	0.02640625	1.03025
5	0.13	2.86	13.58	0.1028	184.4164	0.01056784	1.396024
6	0.16	7.59	11.8	0.1195	139.24	0.01428025	1.4101
7	0.13	4.4	12.44	0.1404	154.7536	0.01971216	1.746576
8	0.15	2.7	15	0.1496	225	0.02238016	2.244
9	0.14	7.3	15	0.125	225	0.015625	1.875
10	0.13	7.12	15	0.125	225	0.015625	1.875
11	0.15	5.2	17.56	0.1404	308.3536	0.01971216	2.465424
12	0.13	5.16	16.42	0.1028	269.6164	0.01056784	1.687976
13	0.15	6.5	18.2	0.1195	331.24	0.01428025	2.1749
14	0.15	3.6	23.66	0.1625	559.7956	0.02640625	3.84475
15	0.12	4.47	23.66	0.0875	559.7956	0.00765625	2.07025
f		0.18153327	-0.00726443	0.07606696	-4.1628^E-05	-4.03587759	0.07061388
k		22.9357536	-0.49688348	-180.553539	0.00708782	675.089775	0.12354873

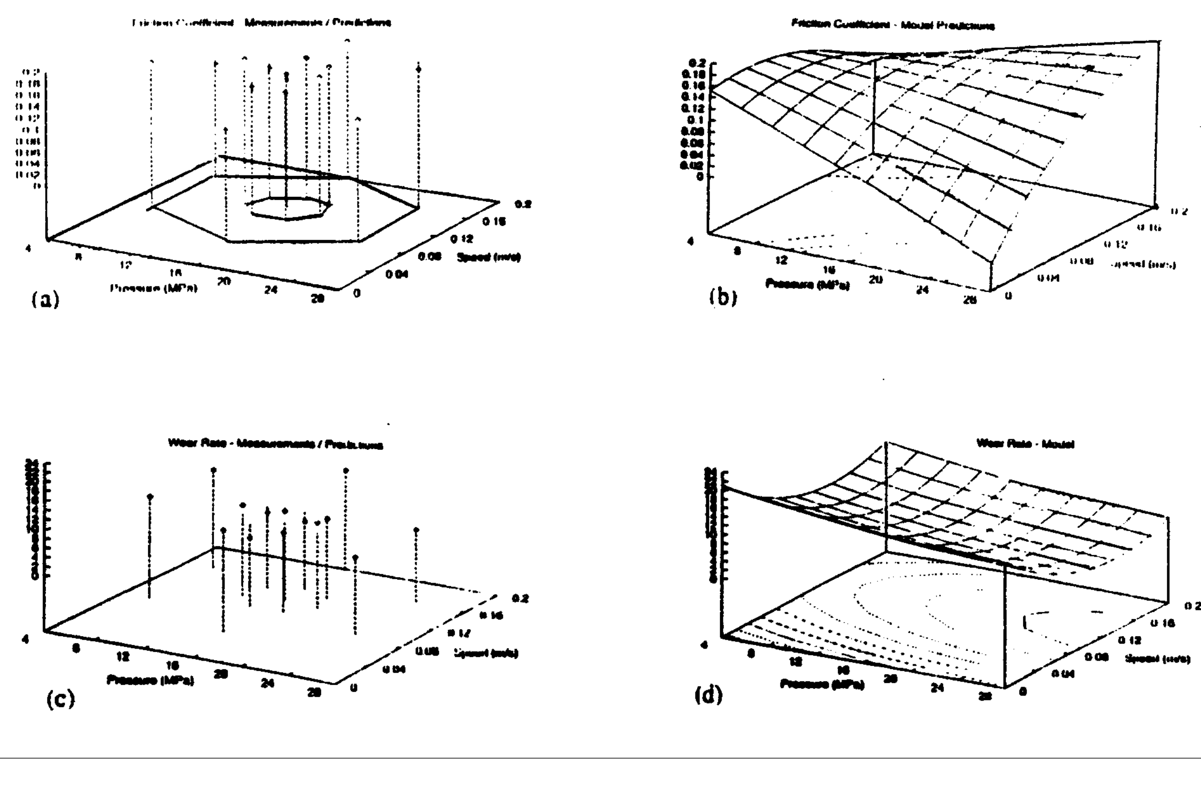

Figure 2 – PCTFE / Al 2024 at 77 K

a) Coefficient of friction, distribution of experimental points
b) Coefficient of friction, response surface
c) Wear rate, distribution of experimental points
d) Wear rate, response surface

Table 2

Second-order model							
r^2 = 0.660866296		s = 0.01367115		r^2 = 577920118		s = 1.993115067	
f_m	Residues f_m	Residues %	Residues Nf_m	k_m	Residues k_m	Residues %	Residues N k_m
0.109874	- 0.009874	- 9.874468	- 0.722285	9. 829969	0.100031	1.007364	0.050188
0.128820	0.011180	7.985479	0.817756	8.340789	0.609211	6.806824	0.305658
0.148733	0.011267	7.042056	0.824165	9.509171	0.420829	4.237952	0.211141
0.112342	- 0.012342	- 12.341926	- 0.902772	8.684337	0.145663	1.649641	0.073083
0.138953	- 0.008953	- 6.887054	- 0.654895	6.240999	- 3.380999	- 118.216755	- 1.696339
0.141046	0.018954	11.846297	1.386429	6.297955	1.292045	17.022993	0.648254
0.139178	- 0.009178	- 7.060026	- 0.671343	6.024936	- 1.624936	- 36.930365	- 0.815275
0.142714	0.007286	4.857347	0.532949	5.452311	- 2.752311	- 101.937441	- 1.380909
0.142049	- 0.002049	- 1.463721	- 0.149893	5.287999	2.012001	27.561657	1.009476
0.142049	- 0.012049	- 9.268623	- 0.881360	5.287999	1.832001	25.730351	0.919165
0.146351	0.003649	2.432883	0.266936	4.658394	0.541606	10.415504	0.271739
0.135391	- 0.005391	- 4.147163	- 0.394357	5.469802	- 0.309802	- 6.003919	- 0.155436
0.140566	0.009434	6.289057	0.690036	4.573251	1.926749	29.642291	0.966702
0.163635	- 0.013635	- 9.089762	- 0.997330	4.108871	- 0.508871	- 14.135318	- 0.255315
0.108298	0.011702	9.751669	0.855963	4.773216	- 0.303216	- 6.783363	- 0.152132

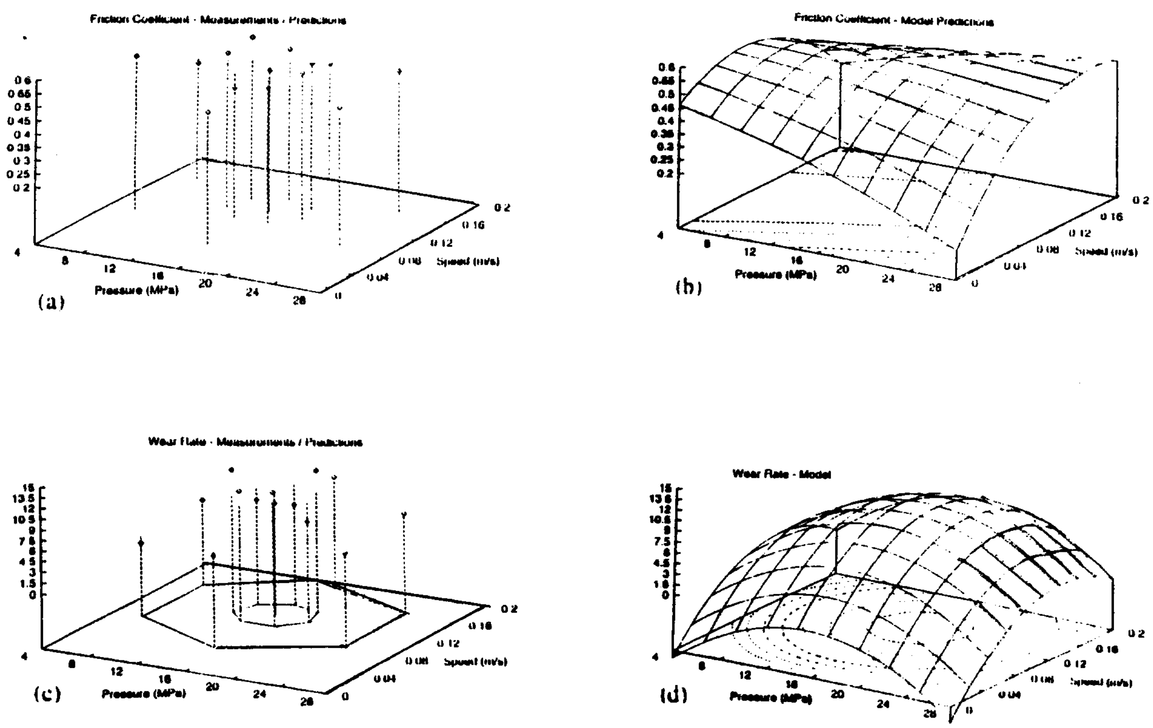

Figure 3 – Polyimide/A286 under reciprocating motion at room temperature

(a) Coefficient of friction, distribution of experimental points
(b) Coefficient of friction, response surface
(c) Wear rate , distribution of experimental points
(d) Wear rate, response surface

From the statistical analysis and the derived equations, comments similar to the preceding example may be made :

- again, the friction coefficient decreases as the contact pressure increases ;
- the friction coefficient varies around 0.50 ; this is a rather high value, contrasting with the runch lower value (0.24) quoted in space applications [Ref 8] and probably due to the detrimental effect of ambient air and humidity ;
- the wear rate is at the limit of acceptability ($\approx 8 \times 10^{-6}$ mm^3/Nm) for space applications, again contrasting with the value of 0.15 found in [Ref 8] ;
- the statistical results are very close to these of the first example : $r^2 = 0.57$ and $s = 0.04$ for f and $r^2 = 0.55$ and $s = 2.6$ for k.

4.3. Discussion

The test plan method proved very useful as a tool in tribological programmes : it offers a firm foundation to study the influence of parameters within wide ranges, while reducing the number of tests required to reach a good reliability of the data ; the statistical analysis allows the evaluation of individual test results and of the quality of the fit between experimental and computed values.

As already mentioned in [Ref. 2], this fit is illustrated on figures where both types of results are plotted as functions of pressure and speed. As a consequence, the engineer/designer can use the appropriate formulas to calculate values of the friction coefficient and of the wear rate under the exact applicable conditions.

Together with the work in progress with other pairs, earlier statements may be confirmed :

a) at room temperature, the polyimide is much more wear resistant than PCTFE ;
b) under LN_2 both polymers are extremely wear-resistant and their friction coefficients are rather similar ;
c) when comparing with results obtained under continuous motion, alternating motion within the studied parameter ranges is always less-demanding.

5. CONCLUSIONS

To summarise, very encouraging results are presented in modelling the tribological behaviour of a seal and its counterpart under very severe operating conditions of temperature, contact pressure and sliding speed. It is simple and provides design guidelines for applications within wide ranges of the parameters. Experiments are underway with other tribological pairs.

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