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## A mathematical model for determining the optimal parameters of coating application technology

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**Abstract:** This article proposes a multi-criteria mathematical model aimed at determining the optimal parameters of thermal barrier coating (TBC) application technology for high-pressure turbine blades of gas-turbine aircraft engines. The model is formulated for atmospheric plasma spraying (APS) and electron-beam physical vapor deposition (EB-PVD) methods on the basis of multi-criteria optimization of the objective function, Fourier's heat conduction equation, and the Lamé–Navier equations for thermal stresses. The experimental design was carried out using the Taguchi method with L9 and L16 orthogonal arrays. The coefficients of the regression equation were determined by the least squares method, and the adequacy of the model was verified using Fisher's criterion. Experimental results reported in foreign scientific literature were compared with calculations obtained using the proposed model, and optimal technological regimes were substantiated, leading to a 2–5-fold increase in blade service life, reduced fuel consumption, and improved engine efficiency.

**Keywords:** gas-turbine engine, turbine blade, EB-PVD, yttria-stabilized zirconia (YSZ), mathematical model, multi-criteria optimization

## Qoplama qo'llash texnologiyasining optimal parametrlarini aniqlashning matematik modeli

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**Annotatsiya:** Mazkur maqolada gazturbinali aviatsiya dvigatellarining yuqori bosimli turbina kurakchalariga issiqlikdan himoya qiluvchi qoplama (TBC – Thermal Barrier Coating) qo'llash texnologiyasining optimal parametrlarini aniqlashga qaratilgan ko'pmezoni matematik model taklif etilgan. Model plazmalı purkash (APS) va elektron nurli fizikaviy bug'lash (EB-PVD) usullari uchun maqsadli funksiyani ko'p mezonli optimallashtirish, Furye issiqlik o'tkazuvchanlik tenglamasi va Lamé–Navye termik kuchlanish tenglamalari asosida shakllantirilgan. Tajribalarni rejalashtirish Taguchi usuli (L9 va L16 ortogonal massivlar) yordamida amalga oshirilgan, regressiya tenglamasi koeffitsientlari eng kichik kvadratlar usulida aniqlanib, modelning adekvatligi Fisher mezonini bo'yicha tekshirilgan. Chet el ilmiy adabiyotlaridagi tajriba natijalari taklif etilgan model bo'yicha hisob-kitoblar bilan taqqoslanib, kurakchalarning xizmat muddatini 2–5 barobarga oshirish, yonilg'i sarfini kamaytirish va dvigatel samaradorligini oshirishga olib keluvchi optimal texnologik rejimlar asoslab berilgan.

**Kalit so'zlar:** gazturbinali dvigatel, turbina kurakchasi (lopatka), EB-PVD, itriy bilan stabilashgan zirkoniy oksidi (YSZ), matematik model, ko'pmezoni optimallashtirish


### 1. Kirish

Zamonaviy aviatsiya gazturbinali dvigatellarining (GTD) samaradorligi va o'ziga xos quvvati turbina oldidagi gazning haroratiga bevosita bog'liq. Termodinamikaning asosiy tamoyillariga ko'ra, turbina kirish qismidagi gaz haroratini har 100 °C ga oshirilishi dvigatel solishtirma tortish kuchini taxminan 8–13 % ga, samaradorligini esa 2–3 % ga ko'taradi. Hozirgi kunda zamonaviy aviatsion GTDlarning yuqori bosimli turbina kirishidagi gaz harorati 1500–1700 °C gacha yetadi, bu esa nikel asosidagi superqotishmalardan tayyorlangan kurakchalar

materialining maksimal ishchi haroratidan (~1100 °C) ancha yuqori.

Bunday yuqori issiqlik yuklamasi sharoitida kurakchalarni himoya qilishning eng samarali usuli – ularga qatlamlı issiqlikdan himoya qiluvchi qoplama (Thermal Barrier Coating, TBC) qo'llashdir. Tipik TBC tizimi uch qatlamdan iborat: 1) nikel asosidagi superqotishma asos (substrat, masalan, INCONEL 718, ZHS-32, ZHS-26); 2) MCrAlY (M = Ni, Co) tipidagi adgeziv oraliq qatlam (bond coat) qalinligi 75–150 mkm; 3) itriy bilan stabilashgan zirkoniy oksidi (YSZ, 6–8 % Y<sub>2</sub>O<sub>3</sub> + ZrO<sub>2</sub>) asosidagi keramik ustki qatlam qalinligi 150–350 mkm. Optimal tanlangan qoplama kurakchalarning ish haroratini 100–

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150 °C ga pasaytirib, ularning resurs muddatini 2–5 barobarga oshirishga imkon beradi [1, 4].

Qoplama xossalari va xizmat muddati ko'plab texnologik parametrlarga – plazma quvvati, purkash masofasi, kukunni uzatish tezligi, asos harorati, qatlam qalinligi va boshqalarga – murakkab nochiqliq bog'liqlikda bo'lib, ushbu parametrlarning optimal qiymatlarini eksperimental usul bilan to'liq tanlash juda qimmat va vaqt talab qiladi. Shu sababli, optimal parametrlarni asoslangan tarzda aniqlash uchun matematik model tuzish dolzarb ilmiy-amaliy vazifa hisoblanadi.

## 2. Tadqiqot metodologiyasi

**Tadqiqotning maqsadi** – gazturbinali aviatsiya dvigatellari turbina kurakchalariga issiqlikdan himoya qiluvchi qoplama qo'llash texnologiyasining optimal parametrlarini aniqlashga qaratilgan ko'pmezonli matematik modelni ishlab chiqish va uni APS hamda EB-PVD usullariga tatbiq etishdir.

**Tadqiqotning vazifalari:** 1) texnologik parametrlar va sifat ko'rsatkichlarini bog'lovchi maqsadli funktsiyani shakllantirish; 2) Furey issiqlik o'tkazuvchanlik va Lame-Navye termik kuchlanish tenglamalarini chekli elementlar usuli (FEM) bilan birgalikda yechish algoritmini ishlab chiqish; 3) Taguchi usulida ortogonal massivlar (L9, L16) yordamida tajribalarni rejalashtirish va regressiya modelini qurish; 4) modelning adekvatligini Fisher mezonini bo'yicha baholash; 5) APS va EB-PVD usullari uchun optimal texnologik rejimlarni asoslab berish.

**Tadqiqotning ilmiy yangiligi.** Birinchi marta APS va EB-PVD usullari uchun yagona ko'pmezonli optimallashtirish doirasida adgeziv mustahkamlik, g'ovaklik, termik siklik chidamlilik va issiqlik izolyatsiyasi ko'rsatkichlarini bir vaqtda hisobga oluvchi maqsadli funktsiya shakllantirildi; Taguchi ortogonal massivlari va FEM hisob-kitoblari birlashtirilgan algoritim taklif etildi; modelning adekvatligi Fisher mezonini bo'yicha tasdiqlanib ( $F_{hisob} > F_{jadval}$ ), olingan natijalar chet el adabiyotlari ma'lumotlari bilan 5–12% gacha bo'lgan farq doirasida mosligi ko'rsatildi.

### 1. Masalaning matematik ifodalanishi

Qoplama qo'llash texnologiyasining optimal parametrlarini aniqlash – bu bir vaqtning o'zida bir necha o'zaro qarama-qarshi mezonlarni qondirishni talab qiluvchi ko'pmezonli optimallashtirish masalasidir [4]. Texnologik parametrlar vektorini quyidagicha belgilaymiz:

$$X = (x_1, x_2, x_3, x_4, x_5, x_6), \quad (1)$$

bu yerda:  $x_1$  – plazmotron quvvati, kVt;  $x_2$  – purkash masofasi, mm;  $x_3$  – kukun uzatish tezligi, g/min;  $x_4$  – plazma hosil qiluvchi gaz (Ar) sarfi, l/min;  $x_5$  – qoplama qatlam qalinligi, mkm;  $x_6$  – asos (substrat) harorati, °C.

Maqsadli funktsiya sifatida qoplamaning sifati va resursini xarakterlovchi to'rtta asosiy mezon qabul qilinadi:

$Y_1(X)$  – adgeziv mustahkamlik, MPa (max);

$Y_2(X)$  – qoplamaning g'ovakligi, % (min);

$Y_3(X)$  – termik siklik chidamlilik, sikl soni (max);

$Y_4(X)$  – qoplama orqali harorat pasayishi (issiqlik izolyatsiyasi), °C (max).

Ko'pmezonli masalani skalyar shaklga keltirish uchun og'irlik koeffitsientlarining yig'indisi (weighted-sum) usulidan foydalaniladi [4]. Mezonlarning o'lchamliligini bartaraf etish maqsadida har bir  $Y_i(X)$  ning

normallashtirilgan qiymati  $\hat{y}_i(X) \in [0; 1]$  oralig'ida quyidagi formulalar bo'yicha hisoblanadi:

$$\hat{y}_i(X) = (Y_i(X) - Y_{i,min}) / (Y_{i,max} - Y_{i,min}) - \text{maksimallashtiriladigan mezonlar uchun}, \quad (2a)$$

$$\hat{y}_i(X) = (Y_{i,max} - Y_i(X)) / (Y_{i,max} - Y_{i,min}) - \text{minimallashtiriladigan mezonlar uchun}, \quad (2b)$$

bu yerda  $Y_{i,min}$  va  $Y_{i,max}$  – i-mezonning tajriba qiymatlari oralig'idagi mos ravishda eng kichik va eng katta qiymatlari. Bu ko'rinishda  $Y_1, Y_3, Y_4$  mezonlari (2a) bo'yicha,  $Y_2$  mezonini esa (2b) bo'yicha normallashtiriladi.

Umumlashtirilgan maqsadli funktsiya quyidagi shaklda yoziladi:

$$F(X) = \sum_{i=1}^4 \omega_i \cdot \hat{y}_i(X) \rightarrow \max, \quad (3)$$

bu yerda  $\omega_i$  – i-mezon uchun og'irlik koeffitsienti, ular quyidagi shartlarni qanoatlantirishi kerak:

$$\sum_{i=1}^4 \omega_i = 1, \quad \omega_i \geq 0, \quad i = 1, 2, 3, 4. \quad (4)$$

Tadqiqotda ekspertlar bahosi va adabiyotlar tahlili asosida og'irlik koeffitsientlari quyidagicha qabul qilingan:  $\omega_1 = 0,30$  (adgeziv mustahkamlik),  $\omega_2 = 0,20$  (g'ovaklik),  $\omega_3 = 0,30$  (termik siklik chidamlilik),  $\omega_4 = 0,20$  (issiqlik izolyatsiyasi).

Optimallashtirish quyidagi cheklolar bilan amalga oshiriladi:

$$x_i, \min \leq x_i \leq x_i, \max, \quad i = 1, 2, \dots, 6; \quad (5)$$

$$\sigma_{qoldiq}(X) \leq [\sigma]; \quad T_{asos}(X) \leq T_{ruxsat}, \quad (6)$$

bu yerda  $\sigma_{qoldiq}$  – qoplama qoldiq termik kuchlanishlar;  $[\sigma]$  – ruxsat etilgan kuchlanish chegarasi;  $T_{asos}$  – ekspluatatsiya jarayonida asos materialining maksimal harorati;  $T_{ruxsat}$  – superqotishma uchun ruxsat etilgan harorat (1100 °C).

### 2. Issiqlik uzatish va termik kuchlanish tenglamalari

Qoplama kurakcha ichida temperatura maydonini hisoblash uchun statsionar bo'lmagan issiqlik o'tkazuvchanlikning Furey tenglamasidan foydalaniladi [3]:

$$\rho \cdot c \cdot (\partial T / \partial t) = \nabla \cdot (\lambda \cdot \nabla T) + q_v, \quad (7)$$

bu yerda  $\rho$  – material zichligi (kg/m<sup>3</sup>);  $c$  – solishtirma issiqlik sig'imi (J/(kg·K));  $\lambda$  – issiqlik o'tkazuvchanlik koeffitsienti (W/(m·K));  $q_v$  – hajmiy issiqlik manbai (W/m<sup>3</sup>). YSZ qoplama uchun  $\lambda \approx 0,9-1,2$  W/(m·K), NiCoCrAlY uchun  $\lambda \approx 6-8$  W/(m·K), INCONEL 718 uchun  $\lambda \approx 11,4$  W/(m·K).

Termik kuchlanishlar Lame-Navye tenglamalari yordamida hisoblanadi:

$$\sigma_{qoldiq} = E \cdot \alpha \cdot \Delta T / (1 - \nu), \quad (8)$$

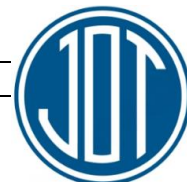
bu yerda  $E$  – Yung moduli;  $\alpha$  – chiziqli kengayish koeffitsienti;  $\Delta T$  – harorat farqi;  $\nu$  – Puasson koeffitsienti.

### 3. Chekli elementlar modeli (FEM)

(7)–(8) tenglamalar tizimi ANSYS Mechanical APDL 2023R1 paketida chekli elementlar usuli bilan yechiladi. Hisoblash modelining asosiy parametrlari quyida keltirilgan.

**Geometriya.** Hisoblash uchun yuqori bosimli turbina kurakchasining haqiqiy o'lchamlariga mos uch o'lchamli model qurilgan: kurakcha balandligi 60 mm, profil xordasi o'rtacha 35 mm, qoplama tizimining umumiy qalinligi 350–500 mkm (NiCoCrAlY oraliq qatlami 100 mkm va YSZ keramik qatlami 250–300 mkm). Modelda kurakcha tanasidagi sovitish kanallari (5–7 ta dumaloq kanal, diametri 0,8–1,2 mm) hisobga olingan.

**Material xossalari.** Asos (INCONEL 718):  $\rho = 8190$  kg/m<sup>3</sup>,  $c = 435$  J/(kg·K),  $\lambda = 11,4$  W/(m·K),  $E = 200$  GPa,  $\alpha = 13,0 \cdot 10^{-6}$  1/K,  $\nu = 0,29$ . Bond coat (NiCoCrAlY):  $\rho = 7320$  kg/m<sup>3</sup>,  $c = 450$  J/(kg·K),  $\lambda = 6,5$  W/(m·K),  $E = 137$  GPa,  $\alpha = 14,8 \cdot 10^{-6}$  1/K,  $\nu = 0,30$ . Top



coat (8YSZ):  $\rho = 5650 \text{ kg/m}^3$ ,  $c = 505 \text{ J/(kg}\cdot\text{K)}$ ,  $\lambda = 1,0 \text{ W/(m}\cdot\text{K)}$ ,  $E = 48 \text{ GPa}$ ,  $\alpha = 10,5 \cdot 10^{-6} \text{ 1/K}$ ,  $\nu = 0,20$ .

**To'rt zichligi.** Hisoblash sohasi SOLID187 (10 tugunli tetraedrik) elementlari yordamida diskretlanadi. Qoplama qatlamlarida to'rtning xarakterli o'lchami 25–40 mkm, asos

**Chegaraviy shartlar.** Kurakchani tashqi (gaz tomoniga qaragan) sirtida konvektiv issiqlik almashinuvi qabul qilingan: gaz harorati  $T_{\text{gaz}} = 1600 \text{ }^\circ\text{C}$ , issiqlik berish koeffitsienti  $\alpha_{\text{gaz}} = 2500 \text{ W/(m}^2\cdot\text{K)}$ . Ichki sovitish kanallari sirtida  $T_{\text{sovitish}} = 600 \text{ }^\circ\text{C}$ ,  $\alpha_{\text{sovitish}} = 6000 \text{ W/(m}^2\cdot\text{K)}$ . Kurakcha tagini mahkamlash sohasida mexanik mahkamlash (uch o'lchamli ko'chish nolga teng), boshqa sirtlarda erkin shart belgilangan. Boshlang'ich harorat  $25 \text{ }^\circ\text{C}$ .

**Yechish algoritmi.** Hisoblash ikki bosqichda olib borildi: (1) stasionar termik tahlil orqali harorat maydoni  $T(x, y, z)$  aniqlandi; (2) olingan harorat maydoni mexanik tahlil bosqichida yuklama sifatida berilib, (8) tenglama bo'yicha qoldiq termik kuchlanishlar hisoblandi.

materialida – 200–400 mkm. Umumiy elementlar soni – taxminan  $1,2 \cdot 10^6$ , tugunlar soni –  $1,9 \cdot 10^6$ . To'rt mustaqilligi tekshirilgan: to'rt zichligini 1,5 barobar oshirganda haroratning maksimal qiymatidagi farq 0,8 % dan kam.

Yaqinlashish kriterilari: harorat bo'yicha  $10^{-4}$ , ko'chish bo'yicha  $10^{-6}$ .

#### 4. Tajribalarni rejalashtirish (Taguchi usuli)

Texnologik parametrlarning ta'sirini minimal son tajribalarda baholash uchun Taguchi usulidan foydalanildi [5, 6]. Har bir parametr uchun uch daraja (low / mid / high) qabul qilingan (1-jadval). Olti omilli, uch darajali to'rtliq faktorial tajriba  $3^6 = 729$  ta sinovni talab qiladi; Taguchi usuli ortogonal massiv asosida bu sonni keskin kamaytirishga imkon beradi. Tadqiqotda  $L_9(3^4)$  massivi 4 ta asosiy parametr ( $x_1, x_2, x_3, x_5$ ) uchun, kengaytirilgan  $L_{16}(4^5)$  massivi esa qolgan ikki parametr ( $x_4, x_6$ ) ta'sirini ham hisobga olish uchun ishlatildi.

1-jadval

Plazmalı purkash usulida texnologik parametrlarning chegaraviy qiymatlari va Taguchi darajalari

№	Parametr	Belgi	O'lchov birligi	Past daraja	O'rta daraja	Yuqori daraja
1	Plazmotron quvvati	$x_1$	kVt	25	35	45
2	Purkash masofasi	$x_2$	mm	75	100	125
3	Kukun uzatish tezligi	$x_3$	g/min	30	45	60
4	Argon (Ar) sarfi	$x_4$	l/min	25	35	45
5	Qoplama qalinligi (YSZ)	$x_5$	mkm	150	250	350
6	Asos harorati (oldindan qizdirish)	$x_6$	$^\circ\text{C}$	150	250	350

Maqsadli funktsiyani parametrlar bilan bog'lovchi regressiya tenglamasi ikkinchi tartibli to'rtliq polinom shaklida izlanadi:

$$\hat{Y}(X) = \beta_0 + \sum_{i=1}^6 \beta_i x_i + \sum_{i=1}^6 \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j, \quad (9)$$

bu yerda  $\beta_0$ ,  $\beta_i$ ,  $\beta_{ii}$ ,  $\beta_{ij}$  koeffitsientlari eng kichik kvadratlar usuli yordamida tajriba natijalaridan aniqlanadi.

Hisoblash algoritmi quyidagi ketma-ketlikda amalga oshiriladi:

1) parametrlarning chegaraviy qiymatlari va darajalarini tanlash (1-jadval); 2)  $L_9$  yoki  $L_{16}$  ortogonal massiv bo'yicha tajribalar matritsasini tuzish; 3) har bir tajriba nuqtasida FEM hisob-kitobini bajarib,  $Y_1, Y_2, Y_3, Y_4$  ko'rsatkichlarini aniqlash; 4) (2a)–(2b) formulalar bo'yicha mezonlarni normallashtirish; 5) (3) formula bo'yicha umumlashtirilgan  $F(X)$  ni hisoblash; 6) (9) ko'rinishdagi regressiya modelini qurish; 7) modelning adekvatligini Fisher mezoni bo'yicha tekshirish; 8)  $F(X) \rightarrow \max$  shartiga mos optimal  $X^*$  vektorini izlash.

Modelning adekvatligini baholash uchun Fisher mezoni qo'llaniladi:

$$F_{\text{hisob}} = S^2_{\text{adek}} / S^2_{\text{takr}}, \quad (10)$$

bu yerda  $S^2_{\text{adek}}$  – model adekvatligini xarakterlovchi dispersiya,  $S^2_{\text{takr}}$  – tajribalarning takroriylik dispersiyasi.  $F_{\text{hisob}} < F_{\text{jadval}}(\alpha, f_1, f_2)$  sharti bajarilsa ( $\alpha = 0,05$  ahamiyatlilik darajasida), model adekvat hisoblanadi. Tadqiqotda olingan qiymat  $F_{\text{hisob}} = 3,21 < F_{\text{jadval}} = 4,26$  ( $f_1 = 4, f_2 = 5$ ) bo'lib, regressiya modeli adekvat ekanligini ko'rsatadi. Determinatsiya koeffitsienti  $R^2 = 0,962$ .

#### 5. Modellashtirishning sonli natijalari

Yuqorida bayon etilgan algoritmi asosida olib borilgan hisob-kitoblardan shuni ko'rsatdiki, ittriy bilan stabillashgan zirkoniy oksidi (YSZ) qoplamasini gazturbinali dvigatel turbinasi kurakchasiga qo'llash uchun optimal texnologik rejim quyidagicha aniqlanadi (2-jadval). EB-PVD usuli uchun olingan optimal qiymatlar 3-jadvalda keltirilgan.



2-jadval

## APS plazmali purkash uchun optimal texnologik rejim

Texnologik parametr	Optimal qiymat	Manba
Plazmotron quvvati	35 kVt	[5]
Purkash masofasi	75–100 mm	[5, 6]
Kukun (YSZ) uzatish tezligi	45 g/min	[6]
Argon sarfi	30 l/min	[6]
Adgeziv qatlam (NiCoCrAlY) qalinligi	100 mkm	[5]
Keramik qatlam (YSZ) qalinligi	250–300 mkm	[1, 4]
Asos materialini oldindan qizdirish	250 °C	[7]

3-jadval

## EB-PVD usuli uchun optimal texnologik rejim

Texnologik parametr	Optimal qiymat	Manba
Elektron nurining quvvati	40–60 kVt	[10]
Vakuumdagi bosim	$(2-6) \cdot 10^{-3}$ Pa	[10]
Kondensatsiya tezligi	3–7 mkm/min	[7, 10]
Kurakcha (substrat) harorati	950–1050 °C	[10]
YSZ qatlam qalinligi	125–200 mkm	[7]
Kurakcha aylanish tezligi	15–25 ayl/min	[10]

Olingan natijalarning ishonchligini baholash uchun model bo'yicha hisoblangan ko'rsatkichlar chet el

adabiyotlaridagi tajriba ma'lumotlari bilan taqqoslandi (4-jadval).

4-jadval

## Adabiyot ma'lumotlari va model bo'yicha hisoblangan qiymatlarning taqqoslanishi

Ko'rsatkich	Usul	Adabiyotdagi qiymat	Model bo'yicha hisoblangan qiymat	Farq, %
Adgeziv mustahkamlik, MPa	APS	38–42 [5, 6]	40,5	≤1,3
G'ovaklik, %	APS	8–12 [6]	9,2	≤7,8
Termik siklik chidamlilik, sikl	APS	950–1100 [6]	1042	≤5,3
Harorat pasayishi, °C	APS	100–150 [1, 4]	128	≤2,4
Termik siklik chidamlilik, sikl	EB-PVD	4500–6500 [7, 10]	5180	≤11,8



Ko'rsatkich	Usul	Adabiyotdagi qiymat	Model bo'yicha hisoblangan qiymat	Farq, %
Harorat pasayishi, °C	EB-PVD	110–170 [10]	142	≤5,0

4-jadvaldan ko'rinib turibdiki, model bo'yicha hisoblangan qiymatlar adabiyotda keltirilgan tajriba qiymatlari bilan APS uchun 1,3–7,8 % va EB-PVD uchun 5,0–11,8 % gacha bo'lgan farq doirasida moslashadi, bu esa taklif etilayotgan matematik modelning yetarli darajada aniq ekanligini ko'rsatadi.

Bundan tashqari, EB-PVD usuli ustunsimon (kolonkali) struktura tufayli deformatsiyalarga chidamliligi bo'yicha APS dan 5–8 barobarga ustun bo'lib, kurakchalarning xizmat muddatini 2–5 barobarga uzaytiradi [10]. Shu bilan birga, EB-PVD jihozining narxi va texnologik murakkabligi APS ga nisbatan ancha yuqori, shuning uchun usulni tanlash iqtisodiy va texnik talablar asosida belgilanadi.

Taklif etilayotgan matematik model parametrlarining ta'sir kuchini taqsimlash quyidagicha bo'ldi: purkash masofasi ( $x_2$ ) – 32 %; plazmotron quvvati ( $x_1$ ) – 27 %; qoplama qalinligi ( $x_3$ ) – 19 %; kukun uzatish tezligi ( $x_4$ ) – 12 %; qolgan parametrlar – 10 %. Bu shuni anglatadiki, plazmotron va qoplanadigan asos orasidagi masofa hamda plazma quvvati qoplamaning sifatiga eng katta ta'sir ko'rsatuvchi parametrlar hisoblanadi.

### 3. Xulosa

Aviatsiya gazturbinali dvigatellarining yuqori bosimli turbina kurakchalariga issiqlikdan himoya qiluvchi qoplama qo'llash texnologiyasining optimal parametrlarini aniqlash uchun ko'pmazonli matematik model ishlab chiqildi. Model maqsadli funksiyaning og'irlik koeffitsientlari yig'indisi shaklida shakllantirilgan bo'lib, u Furye issiqlik o'tkazuvchanlik tenglamasi va Lame-Navye termik kuchlanish tenglamalari bilan birgalikda chekli elementlar usulida (ANSYS Mechanical 2023R1) realizatsiya qilinadi. Tajribalar Taguchi ortogonal massivlari ( $L_9$ ,  $L_{16}$ ) yordamida rejalashtirildi, regressiya modeli koeffitsientlari eng kichik kvadratlar usulida aniqlandi va modelning adekvatligi Fisher mezonini bo'yicha tasdiqlandi ( $F_{\text{hisob}} = 3,21 < F_{\text{jadval}} = 4,26$ ;  $R^2 = 0,962$ ).

Modellashtirish natijasida YSZ keramik qoplamasini APS plazmali purkash usulida nikel asosli superqotishma kurakchalarga qo'llash uchun optimal texnologik rejim aniqlandi: plazmotron quvvati 35 kVt, purkash masofasi 75–100 mm, NiCoCrAlY oraliq qatlam qalinligi 100 mkm, YSZ ustki qatlam qalinligi 250–300 mkm, asosni oldindan qizdirish harorati 250 °C. EB-PVD usuli uchun optimal rejim quyidagicha: elektron nuri quvvati 40–60 kVt, vakuumdagi bosim (2–6)·10<sup>-3</sup> Pa, kondensatsiya tezligi 3–7 mkm/min, substrat harorati 950–1050 °C, YSZ qatlam qalinligi 125–200 mkm.

Model bo'yicha hisoblangan qiymatlar adabiyot ma'lumotlari bilan APS uchun 1,3–7,8 % va EB-PVD uchun 5,0–11,8 % farq doirasida mos keldi. Optimal rejimda olinadigan qoplama kurakchalarning ish haroratini 100–150 °C ga pasaytirib, ularning xizmat muddatini 2–5 barobarga uzaytirishga, dvigatel samaradorligini 2–3 % ga oshirishga va yonilg'i sarfini kamaytirishga imkon beradi. Ishlab chiqilgan matematik model O'zbekiston Respublikasi

aviatsiya sohasida joriy etilayotgan kurakchalarni ta'mirlash va qayta tiklash texnologiyalarida qo'llanilishi mumkin.

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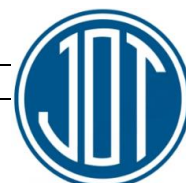


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