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QUYOSH ENERGIYASI QURILMALARINING ISSIQLIK-TEXNIK PARAMETRLARINI MONITORING QILISH UCHUN KO‘P KANALLI AXBOROT OLISH TIZIMINI ISHLAB CHIQISH VA KALMAN FILTRI ASOSIDA O‘LCHASH NOANIQLIGINI KAMAYTIRISH

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Annotatsiya. Maqolada quyosh issiqlik kollektorining kirish va chiqish haroratlarini, kollektor tekisligidagi quyosh nurlanishini va issiqlik tashuvchi sarfini o‘lchaydigan ko‘p kanalli axborot olish tizimining tuzilmasi taklif etilgan. Pt100 termorezistiv datchiklar kanalini raqamlashtirish, diskretlash va raqamli filtrlash bosqichlari matematik modellar asosida asoslab berilgan. Ikki holatli Kalman filtri harorat farqini o‘lchashdagi o‘rtacha kvadratik xatoni 0,141 K dan 0,045 K gacha, ya’ni 68 % ga kamaytirishi hisoblash tajribasida ko‘rsatilgan. Natijada kollektor foydali ish koeffitsiyentining oniy qiymatlaridagi xato 1,61 foiz punktdan 0,51 foiz punktgacha kamaygan. Taklif etilgan yondashuv quyosh qurilmalarini real vaqtda kuzatish tizimlarining metrologik ishonchliligini oshirishga xizmat qiladi.

Kalit so‘zlar: axborot olish tizimi, Pt100, analog-raqamli o‘zgartirgich, diskretlash, Kalman filtri, o‘lchash noaniqligi, quyosh kollektori, IoT monitoring.

Abstract. The paper proposes a multichannel data acquisition system for monitoring the inlet and outlet temperatures, in-plane irradiance and mass flow rate of a solar thermal collector. A two-state Kalman filter reduces the root-mean-square error of the measured temperature difference from 0.141 K to 0.045 K in a computational experiment, lowering the error of instantaneous collector efficiency

from 1.61 to 0.51 percentage points.

Keywords: data acquisition system, Pt100, ADC, sampling, Kalman filter, measurement uncertainty, solar collector.

1. Kirish

O‘zbekiston hududida yillik quyosh nurlanishi resursi yuqori bo‘lib, bu quyosh issiqlik va fotoelektrik qurilmalarini keng qo‘llash uchun qulay sharoit yaratadi [1]. Quyosh issiqlik kollektorlari maishiy issiq suv ta’minoti, isitish va sanoat jarayonlari uchun eng ko‘p tarqalgan quyosh qurilmalari hisoblanadi [2]. Kollektor samaradorligi kirish va chiqish haroratlari, issiqlik tashuvchi sarfi hamda kollektor tekisligiga tushayotgan nurlanish oqimi orqali aniqlanadi [3]. Shu sababli ushbu to‘rt kattalikni uzluksiz va aniq o‘lchash qurilmaning haqiqiy ish ko‘rsatkichlarini baholashning asosiy sharti hisoblanadi [2, 3].

Quyosh qurilmalarini kuzatish uchun datchiklar, ma’lumot yig‘uvchi qurilma, aloqa kanali va dasturiy qatlamdan iborat monitoring tizimlari qo‘llaniladi [4]. Narsalar interneti (IoT) konsepsiyasi bunday tizimlarni datchiklar tarmog‘i, bulutli hisoblash va foydalanuvchi interfeysidan iborat yagona arxitekturaga birlashtirish imkonini bergan [5]. Arduino platformasi va 3G aloqa asosidagi arzon yechim quyosh uy tizimlarini real vaqtda masofadan kuzatishga yaroqli ekani tajribada isbotlangan [6]. Raspberry Pi bortli kompyuteri asosidagi tizim fotoelektrik stansiya parametrlarini bulut serveriga uzatishda ishonchli ishlagan [7]. Fotoelektrik qurilmalar uchun arzon raqamli harorat o‘lchash tizimi ham ishlab chiqilgan va sinovdan o‘tkazilgan [8].

Monitoring tizimlariga qo‘yiladigan metrologik talablar, jumladan o‘lchash kanallari aniqligi va ma’lumot yozish oralig‘i, xalqaro standartlarda belgilangan [9]. Issiqlik kollektorlarini sinash standartida harorat farqini o‘lchash aniqligiga alohida yuqori talab qo‘yilgan, chunki samaradorlik aynan shu kattalikka eng sezgir [10]. Kichik harorat farqlarida datchik va o‘lchash zanjiri shovqini nisbiy xatoni

keskin oshiradi [11, 12]. Bu holat signalni raqamli qayta ishlash usullarini qo‘llashni taqozo etadi [12].

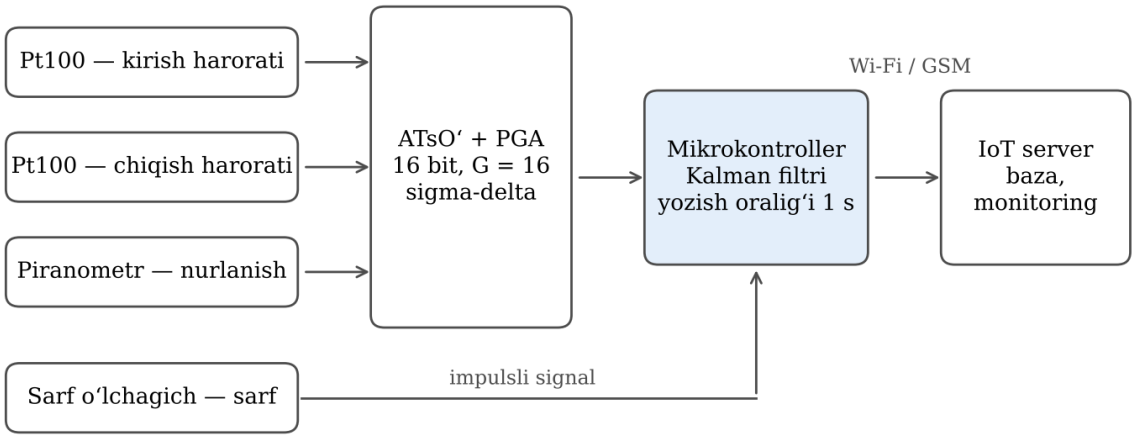
Kalman filtri chiziqli dinamik tizim holatini shovqinli o‘lchovlardan optimal baholash usuli sifatida taklif etilgan [13]. Ushbu usul o‘lchash va jarayon shovqinlari statistikasini hisobga olgani uchun oddiy siljuvchi o‘rtachaga nisbatan kamroq kechikish bilan ishlaydi [14, 15]. Shunga qaramay, ko‘rib chiqilgan IoT monitoring tizimlarining ko‘pchiligida raqamli filtrlash va o‘lchash noaniqligini baholash alohida tadqiq etilmagan [4, 6, 7].

Ushbu ishning maqsadi quyosh kollektori uchun ko‘p kanalli axborot olish tizimi tuzilmasini asoslash va Kalman filtri yordamida harorat farqini o‘lchash noaniqligini kamaytirish samarasini miqdoriy baholashdan iborat [4, 10, 13]. Maqsadga erishish uchun tizim tuzilmasini ishlab chiqish, o‘lchash kanallarini modellashtirish, filtr parametrlarini tanlash va natijalarni GUM qo‘llanmasi asosida baholash vazifalari qo‘yilgan [16, 22].

2. Usullar

2.1. Axborot olish tizimining tuzilmasi

Taklif etilgan tizim to‘rtta o‘lchash kanalini o‘z ichiga oladi: kirish harorati, chiqish harorati, quyosh nurlanishi va massaviy sarf [9, 10]. Harorat kanallarida IEC 60751 standarti bo‘yicha A sinfli Pt100 platinali termorezistorlari ishlatiladi [17]. Nurlanish ISO 9060 bo‘yicha tasniflangan piranometr bilan o‘lchanadi [18]. Sarf impulsli chiqishga ega sarf o‘lchagich orqali aniqlanadi va uning signali mikrokontroller hisoblagichiga bevosita uzatiladi [10, 12]. Analog signallar dasturlanuvchi kuchaytirgichli (PGA) 16 razryadli sigma-delta analog-raqamli o‘zgartirgich (ATsO‘) orqali raqamlashtiriladi [19]. Raqamli ma’lumotlar mikrokontrollerda filtrlanib, simsiz tarmoq orqali IoT serverga uzatiladi [5, 6]. Tizimning umumiy tuzilmasi 1-rasmda keltirilgan [4, 5].



1-rasm. Ko‘p kanalli axborot olish tizimining tuzilmasi

2.2. Termorezistiv o‘zgartirish modeli

Pt100 datchigining 0 °C dan yuqori haroratlardagi qarshiligi Kallendar–Van Dyuzen tenglamasi bilan ifodalanadi [17]:

$$R(t) = R_0(1 + A\,t + B\,t^2), \qquad (1)$$

bu yerda $R(t)$ – datchikning t haroratdagi qarshiligi, Ω; $R_0 = 100\ \Omega$ – datchikning 0 °C dagi nominal qarshiligi; t – harorat, °C; $A = 3{,}9083 \cdot 10^{-3}\ °C^{-1}$ – birinchi tartibli koeffitsiyent; $B = -5{,}775 \cdot 10^{-7}\ °C^{-2}$ – ikkinchi tartibli koeffitsiyent [17].

O‘zgarmas tok bilan ta’minlangan datchikning kuchlanish bo‘yicha sezgirligi quyidagicha aniqlanadi [11, 12]:

$$S = I_0 \frac{dR}{dt} \approx I_0\, R_0\, \alpha, \qquad (2)$$

bu yerda S – kanalning kuchlanish bo‘yicha sezgirligi, V/K; $I_0 = 1$ mA – qo‘zg‘atuvchi tok; $\frac{dR}{dt}$ – qarshilikning harorat bo‘yicha hosilasi, Ω/K; $\alpha = 0{,}00385\ K^{-1}$ – qarshilikning 0–100 °C oralig‘idagi o‘rtacha harorat koeffitsiyenti

[12, 17]. Ushbu parametrlarda kanal sezgirligi $S = 0{,}385\ \mathrm{mV/K}$ ni tashkil etadi [12].

2.3. Kvantlash va diskretlash

ATsO‘ning kvantlash qadami, kvantlash shovqini va ularga mos harorat ekvivalenti quyidagicha topiladi [19]:

$$q = \frac{U_{ref}}{G_{PGA}\, 2^N}, \qquad \sigma_q = \frac{q}{\sqrt{12}}, \qquad \Delta T_q = \frac{q}{S}, \qquad (3)$$

bu yerda q – kvantlash qadami (kichik razryad qiymati), V; U_{ref} – ATsO‘ tayanch kuchlanishi, V; G_{PGA} – dasturlanuvchi kuchaytirgich koeffitsiyenti; N – ATsO‘ razryadlar soni; σ_q – kvantlash shovqinining o‘rtacha kvadratik qiymati, V; ΔT_q – bitta kvantlash qadamiga mos harorat, K [19].

Uzluksiz signalni diskret qiymatlari orqali buzilishsiz tiklash uchun diskretlash chastotasi Kotelnikov–Shennon teoremasi shartini qanoatlantirishi kerak [20]:

$$f_s \geq 2f_{max}, \qquad (4)$$

bu yerda f_s – diskretlash chastotasi, Hz; f_{max} – signal spektrining yuqori chegaraviy chastotasi, Hz [20, 21]. Datchikning issiqlik inersiyasi past chastotali filtr vazifasini bajargani sababli f_{max} datchik vaqt doimiysi orqali baholandi [11].

2.4. Kollektorning issiqlik modeli

Kollektorning foydali issiqlik quvvati va oniy foydali ish koeffitsiyenti quyidagicha hisoblanadi [3, 10]:

$$Q_u = \dot{m}\, c_p (T_{out} - T_{in}), \qquad \eta = \frac{Q_u}{A_c\, G}, \qquad (5)$$

bu yerda Q_u – foydali issiqlik quvvati, W; $\dot{m} = 0{,}03\ \mathrm{kg/s}$ – issiqlik tashuvchining massaviy sarfi; $c_p = 4186\ \mathrm{J/(kg \cdot K)}$ – suvning solishtirma issiqlik

sig‘imi; T_{in} – kollektorga kirish harorati, °C; T_{out} – kollektordan chiqish harorati, °C; η – oniy foydali ish koeffitsiyenti; $A_c = 2{,}0\ m^2$ – kollektor apertura yuzasi; G – kollektor tekisligidagi quyosh nurlanishi, W/m² [3, 10].

Chiqish haroratining dinamikasi birinchi tartibli inersion bo‘g‘in sifatida modellashtirildi [2, 3]:

$$\tau \frac{dT_{out}}{dt} = T_{in} + \frac{A_c[\eta_0 G - a_1(T_m - T_a)]}{\dot{m} c_p} - T_{out}, \qquad (6)$$

bu yerda $\tau = 120\ s$ – kollektorning vaqt doimiysi; $\eta_0 = 0{,}75$ – kollektorning optik samaradorligi; $a_1 = 3{,}5\ W/(m^2 \cdot K)$ – issiqlik yo‘qotish koeffitsiyenti; $T_m = (T_{in} + T_{out})/2$ – issiqlik tashuvchining o‘rtacha harorati, °C; $T_a = 28$ °C – atrof-muhit harorati [3, 10].

Nurlanish 6 soatlik sinusoidal kun profili ko‘rinishida $G_{max} = 900\ W/m^2$ eng katta qiymat bilan berildi va unga davomiyligi 3–5 min bo‘lgan uchta bulut o‘tishi qo‘shildi [1, 3]. Kirish harorati $T_{in} = 30$ °C o‘zgarmas deb qabul qilindi [10]. Har bir harorat kanaliga o‘rtacha kvadratik og‘ishi $\sigma = 0{,}10$ K bo‘lgan oq shovqin qo‘shildi [8, 11]. Hisoblash $\Delta t = 1\ s$ qadam bilan bajarildi, natijalar ISO 9806 tavsiyasiga mos ravishda $G > 300\ W/m^2$ oralig‘ida baholandi [10].

2.5. Kalman filtri

Har bir harorat kanali «harorat – o‘zgarish tezligi» holat vektoriga ega diskret model bilan tavsiflandi [13, 16]:

$$\mathbf{x}_k = \mathbf{F}\,\mathbf{x}_{k-1} + \mathbf{w}_k, \qquad z_k = \mathbf{H}\,\mathbf{x}_k + v_k, \qquad (7)$$

$$\mathbf{F} = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}, \qquad \mathbf{H} = [1 \quad 0], \qquad (8)$$

bu yerda $\mathbf{x}_k = [T_k,\ \dot{T}_k]^T$ – k-qadamdagi holat vektori; T_k – harorat, °C; $\dot{T}_k$ – haroratning o‘zgarish tezligi, K/s; $\mathbf{F}$ – holat o‘tish matritsasi; $\Delta t = 1\ s$ – diskretlash davri; $\mathbf{w}_k \sim \mathcal{N}(0, \mathbf{Q})$ – jarayon shovqini; z_k – k-qadamdagi o‘lchov, °C; $\mathbf{H}$ –

o‘lchash matritsasi; $v_k \sim \mathcal{N}(0, r)$ – o‘lchash shovqini; $r = \sigma^2 = 0{,}01\ K^2$ – o‘lchash shovqini dispersiyasi [13, 14].

Jarayon shovqini kovariatsiyasi oq shovqinli tezlanish modeli bo‘yicha olindi [16]:

$$\mathbf{Q} = q_a \begin{bmatrix} \Delta t^3/3 & \Delta t^2/2 \\ \Delta t^2/2 & \Delta t \end{bmatrix}, \qquad (9)$$

bu yerda $\mathbf{Q}$ – jarayon shovqinining kovariatsiya matritsasi; q_a – tezlanish shovqinining spektral zichligi, K^2/s^3 [15, 16].

Filtrning bashorat va tuzatish bosqichlari quyidagi tenglamalar bilan bajariladi [13, 14]:

$$\hat{\mathbf{x}}_k^- = \mathbf{F}\,\hat{\mathbf{x}}_{k-1}, \qquad \mathbf{P}_k^- = \mathbf{F}\,\mathbf{P}_{k-1}\,\mathbf{F}^T + \mathbf{Q}, \qquad (10)$$

$$\mathbf{K}_k = \mathbf{P}_k^-\mathbf{H}^T(\mathbf{H}\,\mathbf{P}_k^-\mathbf{H}^T + r)^{-1}, \qquad (11)$$

$$\hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_k(z_k - \mathbf{H}\,\hat{\mathbf{x}}_k^-), \qquad \mathbf{P}_k = (\mathbf{I} - \mathbf{K}_k\mathbf{H})\mathbf{P}_k^-, \qquad (12)$$

bu yerda $\hat{\mathbf{x}}_k^-$ – holatning aprior (bashorat) bahosi; $\hat{\mathbf{x}}_k$ – holatning aposterior (tuzatilgan) bahosi; $\mathbf{P}_k^-$ – baholash xatosining aprior kovariatsiyasi; $\mathbf{P}_k$ – baholash xatosining aposterior kovariatsiyasi; $\mathbf{K}_k$ – Kalman kuchaytirish koeffitsiyenti; $\mathbf{I}$ – birlik matritsa [13–15].

Taqqoslash uchun N_w nuqtali siljuvchi o‘rtacha filtri ham qo‘llanildi [21]:

$$\bar{z}_k = \frac{1}{N_w}\sum_{i=0}^{N_w-1} z_{k-i}, \qquad (13)$$

bu yerda $\bar{z}_k$ – k-qadamdagi siljuvchi o‘rtacha qiymat, °C; N_w – oyna uzunligi (nuqtalar soni); z_{k-i} – $(k-i)$-qadamdagi o‘lchov, °C [21].

Filtrlash samarasi o‘rtacha kvadratik xato orqali baholandi [14, 21]:

$$\mathrm{RMSE} = \sqrt{\frac{1}{M}\sum_{k=1}^{M}\left(\Delta\widehat{T}_k - \Delta T_k\right)^2}, \qquad (14)$$

bu yerda RMSE – o‘rtacha kvadratik xato, K; M – baholangan nuqtalar soni; $\Delta\widehat{T}_k$ – filtrlangan harorat farqi, K; $\Delta T_k = T_{out,k} - T_{in,k}$ – modeldagi haqiqiy harorat farqi, K [21].

Foydali ish koeffitsiyentining nisbiy standart noaniqligi GUM qo‘llanmasidagi noaniqlikni tarqatish qonuni bo‘yicha topildi [22]:

$$\frac{u_c(\eta)}{\eta} = \sqrt{\left(\frac{u(\dot{m})}{\dot{m}}\right)^2 + \left(\frac{u(\Delta T)}{\Delta T}\right)^2 + \left(\frac{u(G)}{G}\right)^2 + \left(\frac{u(A_c)}{A_c}\right)^2}, \qquad (15)$$

bu yerda $u_c(\eta)$ – η ning yig‘indi standart noaniqligi; $u(\dot{m})$ – sarfning standart noaniqligi, kg/s; $u(\Delta T)$ – harorat farqining standart noaniqligi, K; $u(G)$ – nurlanishning standart noaniqligi, W/m²; $u(A_c)$ – apertura yuzasining standart noaniqligi, m²; $\Delta T = T_{out} - T_{in}$ – harorat farqi, K [22].

3. Natijalar

Modelda harorat farqi $G > 300\ \mathrm{W/m^2}$ oralig‘ida 3,2 K dan 10,3 K gacha o‘zgardi, uning o‘rtacha qiymati 7,5 K ni tashkil etdi [3, 10]. Bu qiymatlar suvli tekis kollektorlar uchun adabiyotda keltirilgan tipik harorat farqlari oralig‘iga mos keladi [2]. Oniy foydali ish koeffitsiyentining o‘rtacha qiymati 0,72 ga teng bo‘ldi [3].

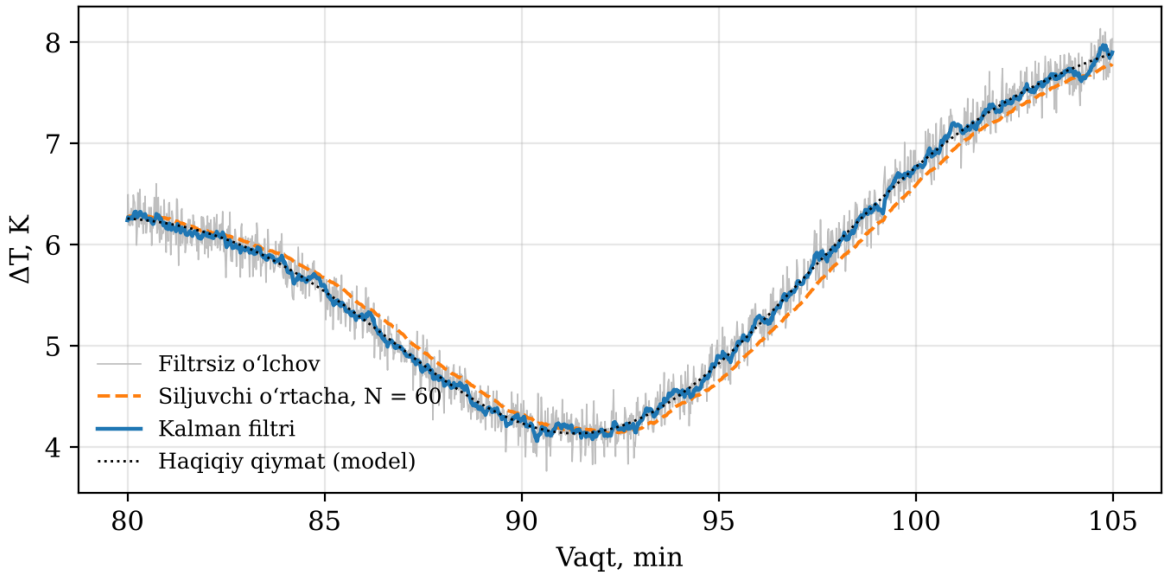
Filtrlanmagan o‘lchovlarda harorat farqining RMSE qiymati 0,141 K bo‘ldi, bu ikki mustaqil kanal shovqinining $\sqrt{2}\,\sigma$ nazariy qiymatiga to‘liq mos keladi [22]. Kalman filtri ($q_a = 10^{-6}\ \mathrm{K^2/s^3}$) bu xatoni 0,045 K gacha, ya’ni 68 % ga kamaytirdi [13, 14]. Shovqinning 20 xil tasodifiy realizatsiyasi bo‘yicha takroriy hisoblashda RMSE qiymati $0{,}0451 \pm 0{,}0007$ K ni tashkil etdi, bu natijaning

barqarorligini ko‘rsatadi [22]. Filtrlash usullarining taqqosiy natijalari 1-jadvalda jamlangan [14, 21].

1-jadval. Harorat farqi va foydali ish koeffitsiyentini baholash xatolari ($G >$ 300 W/m²)

Usul	**RMSE ΔT, K**	**Maks. xato ΔT, K**	**RMSE η, foiz punkt**
Filtrsiz	0,142	0,667	1,61
Kalman, $q_a = 10^{-6}$	0,044	0,172	0,51
Kalman, $q_a = 10^{-5}$	0,059	0,256	0,67
Kalman, $q_a = 10^{-4}$	0,076	0,320	0,87
Siljuvchi o‘rtacha, $N_w = 30$	0,046	0,182	0,55
Siljuvchi o‘rtacha, $N_w = 60$	0,080	0,314	0,99

q_a ortishi bilan filtr o‘lchovga ko‘proq ishonadi va shovqinni kamroq bostiradi, shu sababli xato oshib boradi [15, 16]. Siljuvchi o‘rtacha oynasi 30 dan 60 nuqtagacha kengaytirilganda bulut o‘tishlaridagi kechikish tufayli xato deyarli ikki barobar oshdi [21]. Bu kechikish 2-rasmda bulut o‘tishi davridagi signal parchasida yaqqol ko‘rinadi [14, 21]. Kalman filtri eng yaxshi siljuvchi o‘rtachaga nisbatan RMSE bo‘yicha 3 % ga, maksimal xato bo‘yicha esa 6 % ga ustun keldi [14].



2-rasm. Bulut o‘tishi davrida harorat farqining filtrlanmagan, siljuvchi o‘rtacha va Kalman filtri bilan olingan qiymatlari

(3) formula bo‘yicha 16 razryadli ATsO‘, $U_{ref} = 2{,}5$ V va $G_{PGA} = 16$ bo‘lganda kvantlash qadami $q = 2{,}38$ μV va $\Delta T_q = 0{,}0062$ K ni tashkil etadi [19]. Bu qiymat datchik shovqinidan qariyb 16 marta kichik, ya’ni kvantlash xatosi umumiy noaniqlikka sezilarli hissa qo‘shmaydi [12, 19]. Datchikning gilzadagi vaqt doimiysi 8 s bo‘lganda 40 dB so‘nish uchun diskretlash chastotasi kamida 4 Hz bo‘lishi kerak [11, 20].

GUM bo‘yicha $u(\dot{m})/\dot{m} = 1$ %, $u(G)/G = 1{,}5$ % va $u(A_c)/A_c = 0{,}5$ % qabul qilindi [18, 22]. Individual kalibrlangan harorat kanallari uchun $u(\Delta T) = 0{,}083$ K bo‘lganda η ning nisbiy standart noaniqligi 2,2 % ni tashkil etdi [10, 22]. Kalibrlanmagan A sinf datchiklar uchun esa bu qiymat 3,6 % gacha oshdi [17, 22].

4. Muhokama

Olingan 68 % lik kamayish Kalman filtrining shovqin statistikasi ma’lum bo‘lgan chiziqli tizimlarda o‘rtacha kvadratik ma’noda optimal baho berishi haqidagi nazariy xulosaga mos keladi [13, 15]. Siljuvchi o‘rtacha qisqa oynada Kalman filtriga yaqin natija bergani ham kutilgan holat, chunki sekin o‘zgaruvchi signalda ikkala usul o‘xshash past chastotali filtr vazifasini bajaradi [21]. Kalman

filtrining afzalligi uning tezlik holatini ham baholashi tufayli tez o‘zgarishlarda kechikishni kamaytirishida namoyon bo‘ladi [16]. Bundan tashqari, Kalman filtri $\mathbf{P}_k$ kovariatsiya matritsasi orqali har bir qadamdagi baho noaniqligini ham beradi, bu esa monitoring tizimida ma’lumot sifatini avtomatik nazorat qilish imkonini yaratadi [14, 15].

Adabiyotda keltirilgan IoT monitoring tizimlari asosan ma’lumot uzatish va saqlash vazifalariga e’tibor qaratgan [6, 7]. Arzon harorat o‘lchash tizimlarida esa asosiy e’tibor apparat qismining narxi va soddaligiga berilgan [8]. Monitoring tizimlari bo‘yicha sharhda ham ma’lumot sifatini oshirish usullari kelajakdagi tadqiqot yo‘nalishi sifatida ko‘rsatilgan [4]. Shu jihatdan taklif etilgan yondashuv mavjud tizimlarni metrologik jihatdan to‘ldiradi va IEC 61724-1 talablariga mos ma’lumot sifatini ta’minlashga yordam beradi [9].

Natijalardan kelib chiqadiki, kollektor samaradorligi noaniqligida harorat farqi emas, balki nurlanish o‘lchovi ustun tashkil etuvchiga aylanishi mumkin [18, 22]. Shu sababli kalibrlangan harorat kanallaridan foydalanilganda yuqori sinfli piranometr tanlash keyingi aniqlikni oshirishning asosiy yo‘li hisoblanadi [10, 18].

Tadqiqotning cheklovi shundaki, natijalar sintetik shovqinli matematik model asosida olingan [3, 22]. Real datchiklarda rangli shovqin, vaqt bo‘yicha drift va elektromagnit xalaqitlar ham mavjud bo‘lib, ular filtr parametrlarini moslashtirishni talab etadi [11, 12]. Keyingi bosqichda tizimni ISO 9806 bo‘yicha tajriba stendida sinash va filtr parametrlarini real o‘lchovlar asosida aniqlash rejalashtirilgan [10, 14].

5. Xulosa

1. Quyosh kollektori uchun to‘rt kanalli axborot olish tizimi tuzilmasi va uning o‘lchash kanallari matematik modellari asoslandi [3, 4, 17].

2. 16 razryadli ATsO‘ va $G_{PGA} = 16$ kuchaytirish Pt100 kanalida 0,006 K harorat ajrata olishini ta’minlaydi, bu esa kvantlash xatosini amalda inobatga olmaslik imkonini beradi [19].

3. Ikki holatli Kalman filtri harorat farqi xatosini 0,141 K dan 0,045 K gacha, η xatosini esa 1,61 dan 0,51 foiz punktgacha kamaytiradi [13, 14].

4. Kalman filtri siljuvchi o‘rtachaga nisbatan tez o‘zgaruvchi rejimlarda kichikroq kechikish va maksimal xatoni ta’minlaydi [16, 21].

5. Taklif etilgan usul quyosh qurilmalari monitoringida samaradorlikni real vaqtda ishonchliroq baholash imkonini beradi [9, 10].

Adabiyotlar

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