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TASHQI YUZASI SUV BILAN SOVITILUVCHI QUYOSH FOTOELEKTRIK MODULIDA ISSIQLIK ALMASHINUV JARAYONLARINI SONLI MODELLASHTIRISH

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Annotatsiya. Kirish. *Quyosh fotoelektrik modullarining elektr samaradorligi modul yuzasi haroratiga bog‘liq bo‘lib, harorat ortishi quvvat ishlab chiqarishni kamaytiradi. Shu sababli FEMlarni suv bilan sovitish orqali issiqlik almashinuvini kuchaytirish dolzarb masala hisoblanadi.*

Usul va materiallar. *Tashqi yuzasi suv bilan sovitiluvchi quyosh FEM uchun issiqlik almashinuv jarayonlarini tavsiflovchi matematik model ishlab chiqildi va energiya balansi tenglamalari asosida sonli tadqiqot o‘tkazildi.*

Natijalar. *Suv sarfi 0,01-0,05 kg/s gacha oshirilganda sovituvchi suv harorati 5-8℃ ga kamaydi va modul harorati 40-60 soniyada barqarorlashdi. Suv sarfi 0,005 kg/s dan 0,02 kg/s gacha oshirilganda FEM elektr samaradorligi 2,0-2,5% ga ortdi.*

Xulosa. *Suv bilan sovitish FEM haroratini pasaytirib, elektr energiya ishlab chiqarish samaradorligini oshirish imkonini beradi.*

Kalit so‘zlar: *quyosh fotoelektrik moduli, suv bilan sovitish, issiqlik almashinuvi, energiya balansi, elektr samaradorlik.*

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ ТЕПЛООБМЕНА В СОЛНЕЧНОМ ФОТОЭЛЕКТРИЧЕСКОМ МОДУЛЕ С ВОДЯНЫМ ОХЛАЖДЕНИЕМ ВНЕШНЕЙ ПОВЕРХНОСТИ

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Аннотация. Введение. *Электрическая эффективность солнечных фотоэлектрических модулей напрямую зависит от температуры поверхности модуля, при увеличении которой снижается выработка электрической мощности. В связи с этим интенсификация теплообмена за счёт водяного охлаждения фотоэлектрических модулей является актуальной научно-практической задачей.*

Методы и материалы. *Для солнечного фотоэлектрического модуля с водяным охлаждением внешней поверхности разработана математическая модель процессов* *теплообмена и на основе уравнений энергетического баланса выполнено численное исследование.*

Результаты. *Установлено, что при увеличении расхода охлаждающей воды в диапазоне 0,01-0,05 кг/с температура охлаждающей воды снижается на 5-8℃, а температура модуля стабилизируется в течение 40-60 секунд. При увеличении расхода воды с 0,005 до 0,02 кг/с электрическая эффективность фотоэлектрического модуля возрастает на 2,0-2,5%.*

Заключение. *Водяное охлаждение позволяет снизить температуру фотоэлектрического модуля и повысить эффективность производства электрической энергии.*

Ключевые слова: *солнечный фотоэлектрический модуль, водяное охлаждение, теплообмен, энергетический баланс, электрическая эффективность.*

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NUMERICAL MODELING OF HEAT TRANSFER PROCESSES IN A SOLAR PHOTOVOLTAIC MODULE WITH WATER COOLING OF THE EXTERNAL SURFACE

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Abstract. Introduction. *The electrical efficiency of solar photovoltaic (PV) modules is strongly dependent on the surface temperature of the module, with increasing temperature leading to a reduction in power output. Therefore, enhancing heat transfer through water cooling of PV modules represents a relevant and timely research problem.*

Methods and Materials. *A mathematical model describing heat transfer processes in a solar PV module with water cooling of the external surface was developed, and a numerical investigation was carried out based on energy balance equations.*

Results. *The results show that increasing the cooling water flow rate from 0.01 to 0.05 kg/s reduces the cooling water temperature by 5-8℃, while the module temperature reaches a steady state within 40-60 s. Furthermore, when the water flow rate is increased from 0.005 to 0.02 kg/s, the electrical efficiency of the PV module increases by 2.0-2.5%.*

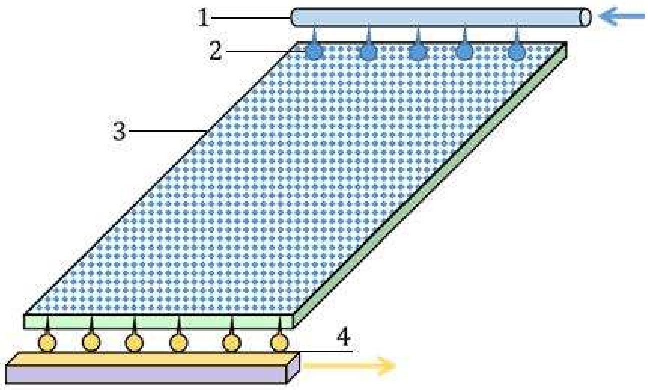
Conclusion. *Water cooling effectively reduces the PV module temperature and enhances the efficiency of electrical power generation.*

Keywords: *solar photovoltaic module, water cooling, heat transfer, energy balance, electrical efficiency.*

Kirish

Quyosh fotoelektrik modullari (FEM) ning ishlash samaradorligi bevosita modul yuzasi haroratiga bog‘liq. Ma’lumki, FEM haroratining ortishi elektr quvvat ishlab chiqarish samaradorligining pasayishiga olib keladi, bu esa butun tizimning energiya balansiga salbiy ta’sir ko‘rsatadi. Shu sababli FEMlarni faol sovitish, xususan, modul tashqi yuzasini suv bilan sovitish orqali issiqlik almashinuv jarayonlarini jadallashtirish muhim muhandislik masalalaridan biri hisoblanadi [1-3]. Quyosh FEMlarida haroratning ortishi elektr samaradorlikni sezilarli darajada pasaytiradi. Xususan, so‘nggi sharh tadqiqotlarida modul harorati har 1℃ ga oshganda samaradorlik taxminan 0,45-0,6% ga kamayishi qayd etilgan. Shu bilan birga, zamonaviy tadqiqotlar suv asosidagi sovitish tizimlari yordamida PV modul yuzasi haroratini 20-46% gacha pasaytirish va elektr samaradorlikni 6-38% gacha oshirish, hatto ishlab chiqarilayotgan quvvatni taxminan 47%

gacha ko‘paytirish mumkinligini ko‘rsatmoqda [4]. Bundan tashqari, maxsus suv purkash tizimlarida modul harorati 61,96℃ dan 36,51℃ gacha pasayib, elektr samaradorlik 10,98% dan 14,47% gacha oshgani kuzatilgan bo‘lib, bu past harorat hisobiga quvvat chiqishining sezilarli darajada ortishiga olib keladi [5]. Ushbu maqolaning asosiy maqsadi tashqi yuzasi suv bilan sovitiluvchi quyosh FEMda issiqlik almashinuv jarayonlarini sonli modellashtirish orqali harorat maydoni, issiqlik oqimi zichligi va sovitish samaradorligini aniqlashdan iborat. Mazkur maqsadga erishish uchun tashqi yuzasi suv bilan sovitiluvchi quyosh FEMning fizik modeli ishlab chiqildi (1-rasm).



1-teshikchali quvur; 2-sovituvchi suv; 3-FEM

1-rasm. FEM yuzasini suv bilan sovitish sxemasi.

Modelda FEM ko‘p qatlamli tuzilma sifatida qaralib, uning asosiy tarkibiy qismlari sifatida shaffof old qoplama, fotoelektrik elementlar, orqa himoya qatlami hamda sovituvchi suv qatlami hisobga olindi. Sonli modellashtirish jarayonini soddalashtirish va hisoblash barqarorligini ta’minlash maqsadida quyidagi asosiy farazlar qabul qilindi: sovituvchi suv oqimi barqaror va laminar rejimda harakatlanadi; suvning fizik xossalari (zichlik, solishtirma issiqlik sig‘imi va issiqlik o‘tkazuvchanligi) doimiy; modul materiallari izotrop va bir jinsli; issiqlik nurlanishi hisobga olinmaydi; quyosh nurlanishi modul yuzasi bo‘ylab bir tekis taqsimlanadi va tizim barqaror issiqlik rejimida ishlaydi. Ushbu farazlar asosida tuzilgan fizik model modul ichidagi harorat taqsimoti, issiqlik oqimi zichligi hamda sovitish jarayonining samaradorligini aniqlash imkonini beradi.

Usul va materiallar

Tashqi yuzasi suv bilan sovitiluvchi quyosh FEMda sovituvchi suv oqimi modul yuzasi bo‘ylab bir yo‘nalishda harakatlanadi deb qabul qilinadi. Sovituvchi suv oqimi uchun energiya balansi quyidagicha ifodalanadi:

$$m_s c_{p,s} \frac{dt_s(t)}{dt} = h_s A_s \big(t_m(t) - t_s(t)\big) - m_s c_{p,s} \big(t_m(t) - t_k\big) \quad (1)$$

bu yerda: m_s-sovituvchi suv massasi, kg; $c_{p,s}$-suvning solishtirma issiqlik sig‘imi, $J/(kg \cdot ℃)$; $t_s(t)$-suv haroratining vaqt bo‘ylab o‘zgarishi, ℃; $t_m(t)$-modul yuzasi haroratining vaqt bo‘ylab o‘zgarishi, ℃; A_s-suv bilan sovitiluvchi modul yuzasi, m^2; m_s-sovituvchi suvning massaviy sarfi, kg/s; t_k-suvning kirishdagi harorati, ℃; h_s-tekis plastina bo‘ylab laminar oqim rejimida suvga konvektiv issiqlik berish koeffitsienti, $W/(m^2 \cdot ℃)$.

Yuqoridagi (1) ifodani standart chiziqli ko‘rinishga keltirish uchun quyidagi amallarni bajaramiz:

$$C = m_s c_{p,s},\ K = h_s A + m_s c_{p,s},\ F = h_s A t_m + m_s c_{p,s} t_k,\ C\frac{dt_s}{dt} + K t_s = F,$$

$$\mu(t) = exp\left(\frac{K}{C}t\right),\ \frac{d}{dt}\left(t_s e^{\frac{K}{C}t}\right) = \frac{F}{C}e^{\frac{K}{C}t},\ t_s e^{\frac{K}{C}t} = \frac{F}{C}\int e^{\frac{K}{C}t}dt + C_1 = \frac{F}{K}e^{\frac{K}{C}t} + C_1,$$

$$t_s(t) = \frac{F}{K} + C_1 e^{-\frac{K}{C}t} \quad (2)$$

Boshlang‘ich shart: $t_s(0) = t_k$, buni (2) ifodaga quysak

$$t_{s,0} = \frac{F}{K} + C_1,\ \text{bundan}\ C_1 = t_{s,0} - \frac{F}{K}$$

$$t_s(t) = \frac{h_s A_s t_m + m_s c_{p,s} t_k}{h_s A_s + m_s c_{p,s}} + \left[t_{s,0} - \frac{h_s A_s t_m + m_s c_{p,s} t_k}{h_s A_s + m_s c_{p,s}}\right] exp\ \left. - \frac{h_s A_s + m_s c_{p,s}}{m_s c_{p,s}}\right) \quad (3)$$

Modul yuzasi harorati uchun nostasionar energiya balansi tenglamasida FEM yupqa plastina sifatida qaraladi va uning yuzasi harorati faqat vaqtga bog‘liq deb qabul qilinadi, shunda modul uchun energiya balansi quyidagi ko‘rinishda yoziladi:

$$m_m c_{p,m} \frac{dt_m(t)}{dt} = (\alpha - \eta_{el}) G A_m - h_s A_m \big(t_m(t) - t_s(t)\big) - h_h A_m \big(t_m(t) - t_h\big) \quad (5)$$

bu yerda m_m-FEMning issiqlik massasiga teng bo‘lgan ekvivalent massa, kg; $c_{p,m}$-modulning solishtirma issiqlik sig‘imi, $J/(kg \cdot ℃)$; $t_m(t)$-modul yuzasi harorati, ℃; α-modul yuzasining quyosh nurlanishini yutish koeffitsienti; η_{el}-FEMning elektr samaradorligi; G-quyosh nurlanishi intensivligi, W/m^2; A_m-modul yuzasi maydoni, m^2; h_s-tekis plastina bo‘ylab laminar oqim rejimida suvga konvektiv issiqlik berish koeffitsienti, $W/(m^2 \cdot ℃)$; $t_s(t)$-sovituvchi suv harorati, ℃; t_h-tashqi havo harorati, ℃; h_h-modul yuzasidan tashqi havoga konvektiv issiqlik berish koeffitsienti, $W/(m^2 \cdot ℃)$.

Quyidagi belgilashlarni kiritamiz:

$$C_m = m_m c_{p,m},\ K_m = (h_s + h_h) A_m,\ F_m = (\alpha - \eta_{el}) G A_m + h_s A_m t_s + h_h A_m t_h$$

$$C_m \frac{dt_m}{dt} + K_m t_m = F_m \quad (6)$$

Integrallovchi ko‘paytuvchi:

$$\mu(t) = exp\left(\frac{K_m}{C_m} t\right),\ \frac{d}{dt}\left(t_m e^{\frac{K_m}{C_m} t}\right) = \frac{F_m}{C_m} e^{\frac{K_m}{C_m} t},\ t_m e^{\frac{K_m}{C_m} t} = \frac{F_m}{K_m} e^{\frac{K_m}{C_m} t} + C_1,\ t_m(t) = \frac{F_m}{K_m} + C_1 e^{-\frac{K_m}{C_m} t} \quad (7)$$

$$t_m(t) = t_{m,\infty} + \left(t_{m,0} - t_{m,\infty}\right) exp\left(-\frac{(h_s + h_h) A_m}{m_m c_{p,m}} t\right) \quad (8)$$

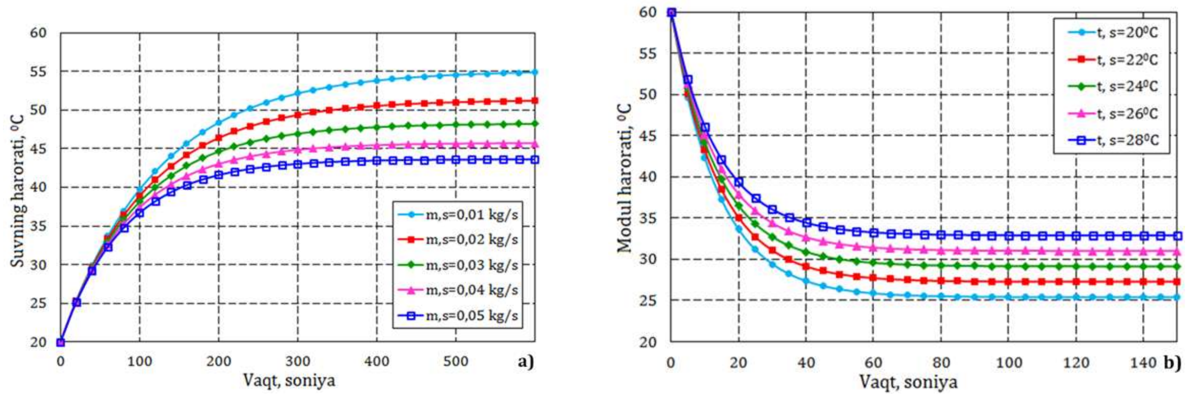
$$t_{m,\infty} = \frac{(\alpha - \eta_{el}) G A_m + h_s A_m t_s + h_h A_m t_h}{(h_s + h_h) A_m} \quad (9)$$

Quyosh FEMning elektr samaradorligini suv sarfiga bog‘liq yakuniy ifodasi:

$$\eta_{el}(m_s) = \eta_{SISh}\left[1 - \beta\left(\frac{(\alpha - \eta_{el}) G + h_s(m_s) t_s + h_h t_h}{h_s(m_s) + h_h} - t_{SISh}\right)\right] \quad (10)$$

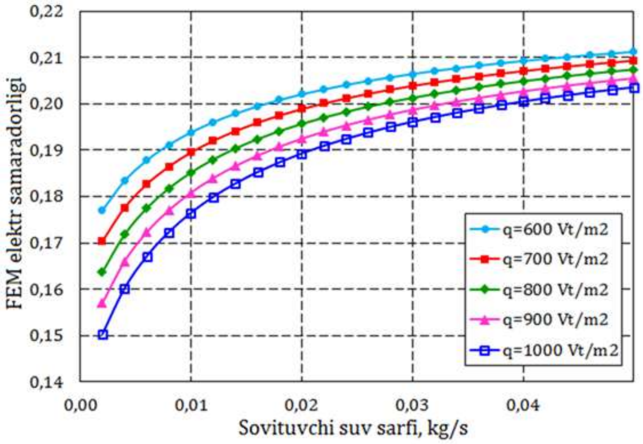
Natijalar va muhokama

Nazariy tadqiqotlar sovituvchi suv sarfi turlicha bo‘lganda suv haroratining vaqt bo‘yicha o‘zgarishini, sovituvchi suv va modul haroratlari o‘zaro bog‘liqligini hamda suv sarfiga bog‘liq holda FEM elektr samaradorligining o‘zgarishini aniqlashga qaratildi (2-rasm).



2-rasm. Sovituvchi suvning chiqish harorati (a) va FEM haroratini (b) o‘zgarishi

2-rasmda sovituvchi suvning chiqish harorati va FEM haroratining suv sarfi hamda kirish haroratiga bog‘liq holda o‘zgarishi keltirilgan. 2-a rasmda barcha suv sarflari uchun sovituvchi suv harorati dastlabki vaqt oralig‘ida tez ortishi va keyinchalik issiqlik almashinuv jarayonining barqarorlashuvi natijasida statsionar qiymatga asimptotik yaqinlashishi kuzatiladi. Suv sarfining ortishi bilan suv haroratining o‘sish tezligi kamayadi hamda statsionar holatdagi yakuniy harorat pasayadi, bu esa suv oqimi intensivligining issiqlikni olib chiqish qobiliyati ortishini ko‘rsatadi. Xususan, suv sarfi 0,01-0,05 kg/s oralig‘ida oshirilganda sovituvchi suvning statsionar harorati taxminan 5-8℃ ga kamayadi. 2-b rasmga ko‘ra, modul harorati sovitish jarayonining dastlabki bosqichida keskin kamayadi va taxminan 40-60 soniya oralig‘ida barqaror rejimga o‘tadi. Statsionar holatda modul harorati sovituvchi suvning kirish haroratiga sezilarli darajada bog‘liq ekanligi aniqlandi. Jumladan, sovituvchi suvning kirish harorati 8°C ga oshirilganda FEMning statsionar harorati o‘rtacha 7,5°C ga ortadi. FEM elektr samaradorligining sovituvchi suv sarfiga bog‘liqligi 3-rasmda keltirilgan.



3-rasm. FEM samaradorligini sovituvchi suv sarfiga bog‘liqligi.

Natijalarga ko‘ra, barcha quyosh nurlanish intensivliklari uchun suv sarfining ortishi bilan FEM elektr samaradorligi monoton ravishda oshadi, biroq ma’lum bir qiymatdan so‘ng samaradorlikning o‘sish sur’ati sezilarli darajada sekinlashadi. Xususan, suv sarfi 0,005 kg/s dan 0,02 kg/s gacha oshirilganda elektr samaradorlik 0,17-0,18 dan 0,195-0,21 gacha ortib, o‘rtacha 2,0-2,5% lik o‘sish ta’minlanadi.

Xulosa

1. Sonli modellashtirish natijalariga ko‘ra, sovituvchi suv sarfi 0,01-0,05 kg/s oralig‘ida oshirilganda sovituvchi suvning statsionar chiqish harorati 5-8°C ga kamayadi, modul harorati esa 40-60 soniya ichida barqaror issiqlik rejimiga o‘tadi.

2. Statsionar holatda FEM harorati sovituvchi suvning kirish haroratiga sezilarli darajada bog‘liq bo‘lib, suvning kirish harorati 8°C ga oshirilganda modulning statsionar harorati o‘rtacha 7,5°C ga ortishi aniqlangan.

3. Sovituvchi suv sarfining ortishi bilan FEM elektr samaradorligi monoton ravishda oshadi; xususan, suv sarfi 0,005 kg/s dan 0,02 kg/s gacha oshirilganda elektr samaradorlik 0,17-0,18 dan 0,195-0,21 gacha ko‘tarilib, o‘rtacha 2,0-2,5% lik qo‘shimcha samaradorlik ta’minlanadi.

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