O‘ZBEKISTON MILLIY UNIVERSITETI XABARLARI, 2025, [3/2/1]
ISSN 2181-7324

FIZIKA
http://journals.nuu.uz
Natural sciences

UDK 621.383.51

Shokir ABILFAYZIYEV,
Termiz davlat muhandislik va agrotexnologiyalar universiteti Aniq va tabiiy fanlar kafedra mudiri, PhD
E-mail: abilfayziyev@inbox.ru

TerDU professori, f-m.f.d. E.To‘rayev taqrizi asosida

MODELING OF HYDRODYNAMIC PROCESSES IN A PHOTOELECTRIC-THERMAL BATTERY USING COMSOL MULTIPHYSICS

Annotation

This article examines the basic principles of Computational Fluid Dynamics (CFD) and its importance in modeling fluid and gas flows. CFD enables the numerical solution of physical equations, making it widely applicable in various engineering and scientific fields. In particular, the complexity of turbulence, the main challenges in its modeling, and existing approaches are analyzed. The article also highlights the use of COMSOL Multiphysics software in modeling CFD processes and its capabilities for solving partial differential equations numerically. By applying these approaches, the movement of liquids and gases and hydrodynamic processes can be analyzed more accurately and efficiently, which is crucial for optimizing technological processes and developing new designs in various industries.

Keywords: photoelectric-thermal battery, mathematical modeling, COMSOL Multiphysics, fluid dynamics, turbulence modeling, Reynolds-averaged Navier–Stokes (RANS), hydrodynamic processes, partial differential equations.

МОДЕЛИРОВАНИЕ ГИДРОДИНАМИЧЕСКИХ ПРОЦЕССОВ В ФОТОЭЛЕКТРИЧЕСКО-ТЕПЛОВОЙ БАТАРЕЕ С ИСПОЛЬЗОВАНИЕМ COMSOL MULTIPHYSICS

Аннотация

В данной статье рассматриваются основные принципы вычислительной гидродинамики (Computational Fluid Dynamics, CFD) и её значение для моделирования течений жидкостей и газов. CFD позволяет решать физические уравнения численными методами и широко применяется в различных инженерных и научных областях. В частности, анализируется сложность турбулентности, основные трудности её моделирования и существующие подходы. Также подчеркивается применение программного обеспечения COMSOL Multiphysics для моделирования процессов CFD и его возможности по численному решению уравнений в частных производных. Использование этих подходов позволяет более точно и эффективно анализировать движение жидкостей и газов, а также гидродинамические процессы, что имеет важное значение для оптимизации технологических процессов и разработки новых конструкций в различных отраслях.

Ключевые слова: фотоэлектрическая-тепловая батарея, математическое моделирование, COMSOL Multiphysics, динамика жидкостей, моделирование турбулентности, усреднённые по Рейнольдсу уравнения Навье–Стокса (RANS), гидродинамические процессы, уравнения в частных производных.

FOTOELEKTRIK-ISSIQLIK BATAREYADAGI GIDRODINAMIK JARAYONLARNING COMSOL MULTIPHYSICS DASTURIDA MODELLASHTIRILISH

Anotatsiya

Ushbu maqolada suyuqliklar dinamikasini hisoblashning (Computational Fluid Dynamics, CFD) asosiy printsiplari va uning suyuqlik va gaz oqimlarini modellashtirishdagi ahamiyati ko‘rib chiqiladi. CFD fizik tenglamalarni sonli usullar orqali yechish imkonini berib, turli muhandislik va ilmiy sohalarda keng qo‘llaniladi. Xususan, turbulentlik hodisasining murakkabligi, uning modellashtirishdagi asosiy qiyinchiliklari va mavjud yondashuvlar tahlil qilinadi. Shuningdek, maqolada COMSOL Multiphysics dasturining CFD jarayonlarini modellashtirishda qo‘llanilishi, uning maxsus qisman differentsial tenglamalar asosida sonli yechimlarni amalga oshirish imkoniyatlari ta’kidlanadi. Ushbu yondashuvlar yordamida suyuqliklar va gazlarning harakati va gidrodinamik jarayonlar aniqroq va samaraliroq tahlil qilinadi, bu esa turli sohalarda texnologik jarayonlarni optimallashtirish va yangi dizaynlarni yaratishda muhim ahamiyat kasb etadi.

Kalit so‘zlar: fotoelektrik-issiqlik batareya, matematik modellashtirish, COMSOL Multiphysics, suyuqlik dinamikasi, turbulentlik modellashtirish, reynolds o‘rtacha Navier-Stokes (RANS), gidrodinamik jarayonlar, qisman differentsial tenglamalar.

Kirish. Suyuqliklar va gazlarning harakati, issiqlik almashinuvi hamda ularning o‘zaro ta’siri muhandislik, fizika, energetika va atrof-muhit fanlarida muhim ahamiyat kasb etadi. Ushbu jarayonlarni aniqlik bilan tahlil qilish va bashoratlashda sonli modellashtirish usullari, xususan COMSOL Multiphysics dasturiy muhiti keng qo‘llanilmoqda. Fotoelektrik-issiqlik batareyalarda yuz beruvchi gidrodinamik jarayonlarni issiqlik almashinuvi va energiya samaradorligi bilan birgalikda modellashtirish esa hanuz yetarli darajada o‘rganilmagan. Shu sababli bu yo‘nalishda sonli tahlil o‘tkazish ilmiy va amaliy jihatdan dolzarbdir.

Turbulentlik jarayonlari suyuqlik dinamikasining eng murakkab masalalaridan biri bo‘lib, ularni modellashtirishda DNS, LES va RANS yondashuvlaridan foydalaniladi. COMSOL Multiphysics platformasi esa chekli elementlar usuli asosida bunday murakkab oqimlarni modellashtirish imkonini beradi.

Mazkur tadqiqotning maqsadi - fotoelektrik-issiqlik batareyadagi gidrodinamik jarayonlarni raqamli modellashtirish, oqim va issiqlik almashinuvi jarayonlarining o‘zaro bog‘liqligini tahlil qilish hamda batareya samaradorligini oshirish yo‘llarini aniqlashdan iborat.

Masalani fizik-matematik qo‘yilishi. Quyosh panellarda issiqlik tarqalishi juda murrakab fizik jarayon xisoblanadi. Sababi bunda bir nechda differensial tenglamalar qo’shib xisoblanadi. Qattiq sirtlarda va suyuqliklarda issiqlik tarqalish tenglamasi, suyuqlik yoki gazlarni xarakati uchun Navier-Stoks tenglamalari birgalikda xisoblanadi. Qattiq jismlarda issiqlik tarqalish tenglamasi quyidagicha yoziladi.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T + \nabla \cdot \vec{q} = Q + Q_{ted} \qquad (1)$$

$$q = -k \nabla T$$

Ushbu tenglama yordamida bir biriga tegib turgan qattiq sirtlarda issiqlik tarqalishi aniqlanadi. Quyosh yerga tushayotgan radiatsiyasini aniqlash uchun quyidagicha tenglama xisoblanadi.

$$J_i = \varepsilon_i e_b(T) FEP_i(T) + \rho_{d,j} G_i$$

$$G_i = G_{m,i} + G_{amb,j} + G_{ext,j} \qquad (2)$$

$$G_{amb,i} = F_{amb,j} \varepsilon_{amb} e_b(T_{amb}) FEP_i(T_{amb})$$

$$e_b(T) = n^2 \sigma T^4,\ FEP_i(T) = \frac{15}{\pi^4} \int_{C_2/(\lambda_i - l^T)}^{C_2/(\lambda_i T)} \frac{x^3}{1 - e^x} dx$$

Suyuqlik yoki gazlarni xarakatini aniqlash uchun Reynolds tomonidan o’rtachalashtirilgan Navier-Stoks differensial tenglamasi qo’llanilgan (RANS). RANS tenglamasini yopish uchun Spallart-Allmares (SA) turbulent modeli qo‘llanilgan.

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \Delta) \mathbf{u} = \Delta \cdot [-\rho \mathbf{l} + \mathbf{K}] + \mathbf{F} \qquad (3)$$

$$\rho \Delta \cdot \mathbf{u} = 0$$

$$\mathbf{K} = (\mu + \mu_T)\left(\Delta \mathbf{u} + (\Delta \mathbf{u})^T\right)$$

$$\frac{\partial \nu^t}{\partial t} + (\mathbf{u} \cdot \Delta) \nu^t = C_{b1} S^T \nu^t - C_{w1} f_w \left(\frac{\nu^t}{l_w}\right)^2 + \frac{1}{\sigma_{\bar{\nu}}} \Delta \cdot \left(\left(\nu + \nu^T\right) \Delta \nu^T\right) + \frac{C_{b2}}{\sigma_{\bar{\nu}}} \Delta \nu^T \cdot \Delta \nu^T$$

$$\Delta G \cdot \Delta G + \sigma_w G (\Delta \cdot \Delta G) = (1 + 2\sigma_w) G^4,\ \ l_w = \frac{1}{G} \cdot \frac{l_{ref}}{2}.$$

SA modelini o’zgarmas konstantalari [12] maqolada berilgan. Ushbu tenglama yordamida suyuqlik oqimini tezliklari va bosimi aniqlanadi. Suyuqlikda issiqlik tarqalish tenglamasi quyidagicha yoziladi.

$$\rho C_p \frac{\partial T_2}{\partial t} + \rho C_p \mathbf{u} \cdot \Delta T_2 + \Delta \cdot \mathbf{q} = Q + Q_p + Q_{vd} \qquad (4)$$

$$\mathbf{q} = -k \Delta T_2$$

4-tenglama 1-tenglamaga o‘xshash asosiy farqi suyuqlik oqimida tezlikni xisobga olivchi konvektiv xad qo’shiladi. Konvektiv issiqlik almashuvidan olingan issiqlik berish koeffitsiyenti:

$$h = \frac{k}{D_h} Nu \qquad (5)$$

bunda k – issiqlik tashuvchining issiqlik o’tkazuvchanlik koeffisienti; Nu – Nusselt soni D_h – ekvivalent diametr hisoblanib, quyidagicha aniqlanadi:

$$D_h = \frac{4Wd}{2(W + d)} \qquad (6)$$

bunda d – kanalning ekvivalent diametri (m). $\mathrm{Re} < 340$

$$Nu = 5.4 + \frac{0.00190\left[\mathrm{Re}\,\mathrm{Pr}\left(\frac{D_h}{L}\right)\right]^{1.71}}{1 + 0.0053\left[\mathrm{Re}\,\mathrm{Pr}\left(\frac{D_h}{L}\right)\right]^{1.71}} \qquad (7)$$

bunda Re – Reynolds soni; Pr – Prantdl soni; L – kanal uzunligi va $340 \le \mathrm{Re} \le 3400$

$$Nu = 0.116\left(\mathrm{Re}^{2/3} - 125\right)\mathrm{Pr}^{1/3}\left[1 + \left(\frac{D_h}{L}\right)^{2/3}\right]\left(\frac{\mu}{\mu_w}\right) \qquad (8)$$

Shunday qilib FEB-TEG qurilmasining umumiy FIK,

$$\eta_T = \eta_{PV} + \eta_{th} + \eta_{TEG} \qquad (9)$$

bunda qurilmaning issiqlik qismi FIKi qo‘yidagicha topiladi:

$$\eta_{th} = \frac{mc(T_{out} - T_i)}{A_{PVTE^I T}} \qquad (10)$$

Mos ravishda TEG ning elektrik FIK:

$$\eta_{TEG} = \frac{\alpha^2}{4kR}\left(T_p - T_f\right) \qquad (11)$$

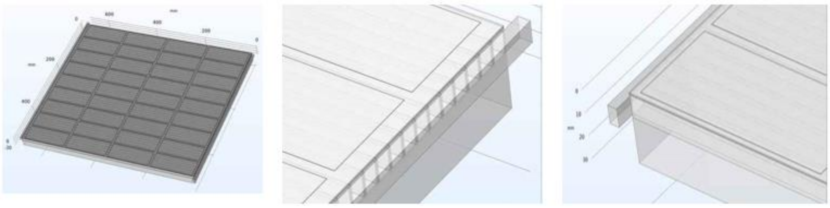
TEGdagi sovuq va issiq yuzalar orasidagi harorat farqidan yuzaga keladigan issiqlik EYUK quyidagicha aniqlanadi:

$$V_\alpha = \alpha\left(T_p - T_f\right) \quad (12)$$

Shunday qilib, TEG hosil qiladigan quvvatni quyidagicha aniqlash mumkin:

$$P = \frac{\left[\alpha\left(T_p - T_f\right)\right]^2}{R_n} \quad (13)$$

Quyosh kollektorini umuniy ko‘rinishi 1-rasmda tasvirlangan.



a) b) c)

1-rasm. a) quyosh kollektorini umuniy ko‘rinishi b) suyuqlik kirish qismi c) suyuqlik chiqish qismi

Yechish usuli va chegaraviy shartlari. COMSOL Multiphysics har xil turdagi fizika muammolarini hal qilish uchun bir qator hal qiluvchilarni taklif qiladi. Yechish vositasini tanlash modellashtirilgan fizika turiga, masalaning murakkabligiga, kerakli aniqlikka va mavjud hisoblash resurslariga bog'liq. RANS va SA turbulentlik modelining tenglamalarini echish uchun to'g'ridan-to'g'ri hal qiluvchi algoritm (PARDISO) yordamida to'liq bog'langan yondashuv (Fully Coupled) ishlatilgan. Damping koeffitsienti 0,1 bo'lgan Nyutonning iterativ usuli qo'llanildi. Iteratsiya jarayoni 250 iteratsiyagacha davom etdi va qolgan muammolar uchun iteratsiya jarayoni 350 iteratsiyagacha davom etdi. Tolerantlik koeffitsienti 1, qoldiq koeffitsienti 1000. Barcha devorlarda yopishqoqlik sharti qo‘llanilgan.

$$\begin{cases}
\dfrac{\partial\rho U}{\partial x}+\dfrac{\partial\rho U}{\partial y}+\dfrac{\partial\rho U}{\partial z}=0,\\
\dfrac{\partial\rho U}{\partial t}+U\dfrac{\partial\rho U}{\partial x}+V\dfrac{\partial\rho U}{\partial y}+W\dfrac{\partial\rho U}{\partial z}=-\dfrac{\partial P}{\partial x}+\left(\mu_t+\mu\right)\left(\dfrac{\partial^2U}{\partial x^2}+\dfrac{\partial^2U}{\partial y^2}+\dfrac{\partial^2U}{\partial z^2}\right)+\rho F_x,\\
\dfrac{\partial\rho V}{\partial t}+U\dfrac{\partial\rho V}{\partial x}+V\dfrac{\partial\rho V}{\partial y}+W\dfrac{\partial\rho V}{\partial z}=-\dfrac{\partial P}{\partial y}+\left(\mu_t+\mu\right)\left(\dfrac{\partial^2V}{\partial x^2}+\dfrac{\partial^2V}{\partial y^2}+\dfrac{\partial^2V}{\partial z^2}\right)+\rho F_y,\\
\dfrac{\partial\rho W}{\partial t}+U\dfrac{\partial\rho W}{\partial x}+V\dfrac{\partial\rho W}{\partial y}+W\dfrac{\partial\rho W}{\partial z}=-\dfrac{\partial P}{\partial z}+\left(\mu_t+\mu\right)\left(\dfrac{\partial^2W}{\partial x^2}+\dfrac{\partial^2W}{\partial y^2}+\dfrac{\partial^2W}{\partial z^2}\right)+\rho F_z,\\
\rho C_p\left(\dfrac{\partial T}{\partial t}+U\dfrac{\partial\rho T}{\partial x}+V\dfrac{\partial\rho T}{\partial y}+W\dfrac{\partial\rho T}{\partial z}\right)=\left(k_t+k\right)\left(\dfrac{\partial^2T}{\partial x^2}+\dfrac{\partial^2T}{\partial y^2}+\dfrac{\partial^2T}{\partial z^2}\right)+Q+Q_p+Q_{vd},\\
\dfrac{\partial\rho\nu^t}{\partial t}+U\dfrac{\partial\rho\nu^t}{\partial x}+V\dfrac{\partial\rho\nu^t}{\partial y}+W\dfrac{\partial\rho\nu^t}{\partial z}=\left(\mu_t+\mu\right)\left(\dfrac{\partial^2\nu^t}{\partial x^2}+\dfrac{\partial^2\nu^t}{\partial y^2}+\dfrac{\partial^2\nu^t}{\partial z^2}\right)+\rho C_{b1}S^T\nu^t-\rho C_{w1}f_w\left(\dfrac{\nu^t}{l_w}\right)^2+\rho\dfrac{C_{b2}}{\sigma_{\bar\nu}}\left(\dfrac{\partial\nu^t}{\partial x}+\dfrac{\partial\nu^t}{\partial y}+\dfrac{\partial\nu^t}{\partial z}\right)^2,\\
k=\dfrac{\mu}{\mathrm{Pr}},\quad k_t=\dfrac{\mu_t}{\mathrm{Pr}_t}.
\end{cases} \quad (14)$$

Bu yerda, $\mu = 0.0165$, $Pr_t = 0.85, Pr = 0.71$

Galerkining eng kichik kvadratlar xadini qo'shish orqali biz quyida ko'rsatilganidek, yuqoridagi tenglama uchun kichik kvadratlar formulasini olamiz:

$$\begin{cases}
\nu\int\limits_\Omega \nabla\mathbf{u}:\nabla\mathbf{v}+\int\limits_\Omega\left(\mathbf{u}.\nabla\mathbf{u}\right).\mathbf{v}-\int\limits_\Omega p\left(\nabla.\mathbf{v}\right)+R_{GLS}=\int\limits_\Omega\mathbf{f}.\mathbf{v},\\
\tilde\nu\int\limits_\Omega\nabla\tilde{\mathbf{u}}:\nabla\tilde{\mathbf{v}}+\int\limits_\Omega\left(\mathbf{u}.\nabla\tilde{\mathbf{u}}\right).\tilde{\mathbf{v}}+\tilde R_{GLS}=\int\limits_\Omega\mathbf{f}.\tilde{\mathbf{v}},\\
T\int\limits_\Omega\nabla T:\nabla t+\int\limits_\Omega\left(\mathbf{u}.\nabla T\right).t+\tilde R_{GLST}=\int\limits_\Omega\mathbf{f}.T,\\
\int\limits_\Omega q\left(\nabla.\mathbf{u}\right)=0.
\end{cases} \quad (15)$$

Bu yerda R_{GLS} va $\tilde R_{GLS}$ quyidagicha aniqlanadi

$$\begin{cases}
R_{GLS}=\tau\left(\mathbf{u}.\nabla\mathbf{v}-\nu\nabla^2\mathbf{v}\right)\left(\mathbf{u}.\nabla\mathbf{u}-\nu\nabla^2\mathbf{u}-\mathbf{f}.\mathbf{v}\right)+\tau_p\left(\nabla q\nabla p\right),\\
\tilde R_{GLS}=\tilde\tau\left(\mathbf{u}.\nabla\tilde{\mathbf{v}}-\tilde\nu\nabla^2\tilde{\mathbf{v}}\right)\left(\mathbf{u}.\nabla\tilde{\mathbf{u}}-\tilde\nu\nabla^2\tilde{\mathbf{u}}-\mathbf{f}.\tilde{\mathbf{v}}\right),\\
\tilde R_{GLST}=\tilde\tau\left(\mathbf{u}.\nabla t-\tilde\nu\nabla^2 t\right)\left(\mathbf{u}.\nabla T-\tilde\nu\nabla^2 T-\mathbf{f}.T\right).
\end{cases} \quad (16)$$

τ va $\tilde\tau$ quyidagicha aniqlanadi

$$\begin{cases}
\tau=\min\left(\dfrac{h}{2\rho\left|\mathbf{u}\right|},\dfrac{h^2}{48\nu}\right),\\
\tilde\tau=\min\left(\dfrac{h}{2\rho\left|\mathbf{u}\right|},\dfrac{h^2}{48\min\left(\tilde\nu_{11},\tilde\nu_{12}\right)}\right).
\end{cases} \quad (17)$$

Bosim uchun τ_p quyidagicha aniqlanadi

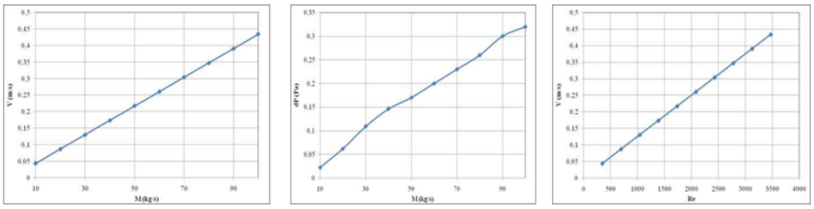
$$\tau_p = \frac{|\mathbf{u}|h}{2}\min\left(1, \mathrm{Re}^h\right). \quad (18)$$

Bu yerda Re^h — Setkadagi Reynolds soni.

$$\mathrm{Re}^h = \frac{|\mathbf{u}|h}{\nu}. \quad (19)$$

Olingan natijalar taxlili. Mazkur tadqiqotda quyosh panellarida issiqlik tarqalishi va suyuqlik oqimi COMSOL Multiphysics dasturida, Navier–Stoks tenglamalari va RANS-Spalart–Allmaras modeli asosida modellashtirildi.

2-rasmda quyosh kollektoriga suvning kirish qismidagi **massaviy sarf**ning turli fizik parametrlar bilan bog‘liqligi tahlil qilingan.

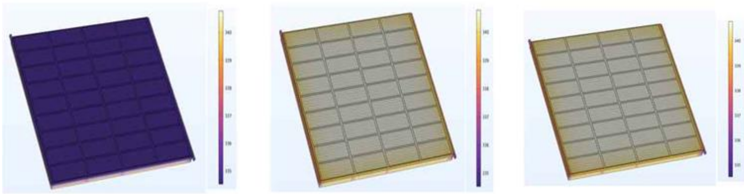


a) b) c)

2-rasm. a) massaviy suv sarfning tezligiga bog‘liqligi b) massaviy sarfning bosim yo‘qotishiga bog‘liqligi; c) massaviy sarfning Reynolds soniga bog‘liqligi

2a-rasmda suv tezligi ortishi bilan massaviy sarfning oshishi tasvirlangan bo’lsa, 2b-rasmda esa massaviy sarf va bosim yo‘qotishlari o‘rtasidagi bog‘liqlik keltirilgan. 2c-rasmda esa Reynolds sonining massaviy sarfga ta’siri ko‘rsatilgan. Natijalar Bernulli va Navier–Stoks tenglamalariga muvofiq ravishda oqim tezligi oshishi bilan massa oqimi va bosim yo‘qotishlarining ortishini tasdiqlaydi.

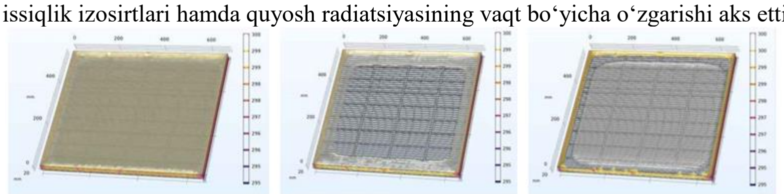
3-rasmda quyosh paneli sirtidagi issiqlik tarqalishining vaqt bo‘yicha o‘zgarishi aks ettirilgan.



Soat 12^{00} Soat 12^{30} Soat 13^{00}

3-rasm. Quyosh sirtidagi issiqlik tarqalishi turli vaqtlarda

3-rasmda quyosh paneli sirtidagi issiqlik tarqalishining vaqt bo‘yicha (12:00, 12:30, 13:00) o‘zgarishi ko‘rsatilgan. 870 W/m² radiatsiya ta’sirida harorat dastlab markaziy qismda ortib, keyin sirt bo‘ylab tengroq taqsimlangan va vaqt o‘tishi bilan pasaygan. 4-rasmda esa issiqlik izosirtlari hamda quyosh radiatsiyasining vaqt bo‘yicha o‘zgarishi aks ettirilgan.



Soat 12^{00} Soat 12^{30} Soat 13^{00}

4-rasm. Turli vaqtlardagi issiqlikni izosirtlari va panel sirtidagi quyosh radiatsiyasi

4-rasmda quyosh paneli sirtidagi issiqlik izosirtlari va radiatsiya taqsimoti keltirilib, panelning termal dinamikasi hamda energiya yutilishining vaqt bo‘yicha o‘zgarishi aks ettirilgan. Natijalar issiqlikning sirt bo‘ylab bir tekis taqsimlanishi samarali ishlash uchun muhimligini, radiatsiya intensivligi va vaqt omili harorat taqsimotiga bevosita ta’sir qilishini ko‘rsatadi. Shuningdek, izosirtlar yordamida sovutish tizimi yoki termoelektr modullarni joylashtirish uchun optimal zonalar aniqlanishi mumkin.

5-rasmda esa kanal bo‘ylab oqim tezligi vektorlarining yo‘nalishi tasvirlangan.

5-rasm. Kanalning turli qismlarda tezlik vektorini yo‘nalishi

5-rasmda suyuqlik (suv) oqimining kanal ichidagi tezlik vektorlari tasvirlangan. Grafik oqimning gidrodinamik holatini ya’ni tezlik taqsimoti, devor yaqinidagi gradientlar va oqim simmetriyasini tahlil qilish imkonini beradi. Kanal kirish qismida oqim nisbatan barqaror bo‘lib, pastga siljish davomida devorlar yaqinida sekinlashgan zonalar kuzatiladi.

Xulosa. Mazkur tadqiqotda quyosh panellarida issiqlik tarqalishi va suyuqlik oqimi COMSOL Multiphysics dasturida, Navier–Stoks tenglamalari va RANS-Spalart–Allmaras modeli asosida modellashtirildi. Tadqiqot natijalari shuni ko‘rsatdiki, quyosh radiatsiyasi intensivligi, kanal geometriyasi va suyuqlik oqimi panel sirt harorati, massaviy sarf va bosim yo‘qotishlariga sezilarli ta'sir qiladi, yil fasllariga qarab sirt va chiqish harorati o'zgarishi esa tizim samaradorligini baholash imkonini beradi. Ushbu natijalar quyosh energiyasidan samarali foydalanish, issiqlik almashuvini optimallashtirish va energiya tizimlarini loyihalashda muhim ahamiyat kasb etadi, shuningdek kelajakda turli sovutish suyuqliklari bilan solishtirma tahlillarni o'tkazish tavsiya etiladi.

ADABIYOTLAR

1. https://oz.sputniknews.uz/20241120/atrof-muhit-yashil-iqtisodiyot-mirziyoev-2025-yil-nom-46708639.html?utm_source=chatgpt.com
2. Orozco Murillo, W., Palacio-Fernande and all. (2020). Analysis of a Jet Pump Performance under Different Primary Nozzle Positions and Inlet Pressures using two Approaches: One Dimensional Analytical Model and Three Dimensional CFD Simulations. *Journal of Applied and Computational Mechanics*, 6(Special Issue), 1228-1244.
3. Hadad, K., Eidi, H. R., & Mokhtari, J. (2017). VOC level control by ventilation improvement of Flexography printing room using CFD modeling. *Journal of Applied and Computational Mechanics*, 3(3), 171-177.
4. Tsega, E. G., & Katiyar, V. K. (2019). A Numerical Simulation of Inspiratory Airflow in Human Airways during Exercise at Sea Level and at High Altitude. *Journal of Applied and Computational Mechanics*, 5(1), 70-76.
5. Spalart P. R., and Venkatakrishnan, V. (2016). On the Role and Challenges of CFD in the Aerospace Industry. *Aeronautical Journal*, Vol. 120, No. 1223, pp. 209–232. doi:10.1017/aer.2015.10
6. Ashton N., Skaperdas V. (2019). Verification and validation of OpenFOAM for high-lift aircraft flows. *Journal of Aircraft*, 56(4), 1641-1657.
7. "Turbulence modeling Resource. NASA Langley Research Center", http://turbmodels.larc.nasa.gov.
8. Spalart P. R., Allmaras S. R. (1992). A one-equation turbulence model for aerodynamic flows. *AIAA Paper* 1992-0439.
9. Menter F. R. (1993). Zonal two-equation k-ω turbulence models for aerodynamic flows. *AIAA Paper* 1993-2906.
10. Menter F. R., Kuntz M., and Langtry R. (2003). Ten Years of Industrial Experience with the SST Turbulence Model. *Turbulence, Heat and Mass Transfer*, 4, 625-632.
11. Pasha, A. A. (2018). Study of parameters affecting separation bubble size in high speed flows using k-ω turbulence model. *Journal of Applied and Computational Mechanics*, 4(2), 95-104.
12. Slotnick, J., Khodadoust, A. and all. (2014). CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences. NASA CR-2014-21878.
13. Abbas-Bayoumi, A., Becker, K. (2011). An Industrial View on Numerical Simulation for Aircraft Aerodynamic Design. *Journal of Mathematics in Industry*, 1(1), Paper 10. doi:10.1186/2190-5983-1-10.