Dynamic simulation of inner flow in a photovoltaic pump based on Simulink and CFD

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ABSTRACT

To study the internal flow characteristics of the photovoltaic pump under the transient change of the solar radiation, the simulation algorithm of the photovoltaic pump system was established by MATLAB/Simulink and CFD for the first time and the results were validated by the test. Firstly, the change rule of pump flow rate and rotation speed under transient solar radiation was obtained by Simulink. Then the results of the change rule were transformed into the boundary condition of CFD by CEL function and the transient flow field in the photovoltaic pump was obtained. The internal flow characteristics and pressure pulsation in the pump were analyzed when the solar radiation increases or decreases transiently. The results demonstrate that the numerical calculation can provide accurate prediction for the characteristics of internal flow in the pump. The numerical results are closed to experimental results, the minimum error of pressure is 0.93% and the maximum error is 1.78%. When the solar radiation increases transiently, the low pressure area at the impeller inlet gets larger obviously and the jet-wake at the impeller outlet becomes more obvious. The pressure pulsation in impeller gradually increases and becomes stable after 0.6 s. The pressure from the impeller outlet to guide vane outlet is stable at 123 kPa. When the solar radiation decreases transiently, the pressure in the impeller takes 1.6 s to be stable. Larger pressure pulsation occurs from the impeller outlet to the guide vane inlet and the maximum differential pressure is 10 kPa. Compared with the transient increase of solar radiation, the pressure in the impeller takes more 0.2 s to stabilize when the solar radiation transient decreases. Meanwhile, the results in this paper can provide references for other transient characteristics research.

Key words: internal flow, numerical simulation, photovoltaic pump, pressure pulsation, transient solar radiation

HIGHLIGHT

- First, the relation between pump flow rate and rotation speed under transient solar radiation was obtained by Simulink. Then the results from Simulink were transformed to be the boundary condition of CFD by CEL function. The internal flow characteristics and pressure pulsation in the pump were analyzed under the instantaneous increase or decrease of the solar radiation.

NOMENCLATURE

\begin{itemize}
\item $\alpha$: Photovoltaic array current temperature coefficient (A/°C)
\item $\beta$: Photovoltaic array voltage temperature coefficient(V/°C)
\item $R_S$: The photovoltaic array resistor($\Omega$)
\item $T_{\text{ref}}$: Photovoltaic array temperature(25°C)
\item $G_{\text{ref}}$: Photovoltaic array solar radiation(1000 W/m\textsuperscript{2})
\item $n$: Pump rotational speed (r/min)
\item $\rho$: Fluid density(kg/ m\textsuperscript{3})
\item $g$: Acceleration of gravity (m/s\textsuperscript{2})
\item $I_{SC}$: Photovoltaic array short-circuit current(A)
\item $I_{m}$: Photovoltaic array current at maximum power point(A)
\item $Q$: Pump flow rate(m\textsuperscript{3}/h)
\item $H$: Pump head(m)
\item $Q_d$: Pump flow rate under design condition(m\textsuperscript{3}/h)
\item $H_d$: Pump head under design condition(m)
\item $\eta$: Pump efficiency(\%)
\item $U_{OC}$: Photovoltaic array open circuit voltage(V)
\end{itemize}

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| Symbol | Mathematical Notation | Description |
|--------|-----------------------|-------------|
| $U_{in}$ | Photovoltaic array voltage at maximum power point(V) |
| $P_n$ | Motor rated power(W) |
| $V_n$ | Motor line voltage(V) |
| $f_n$ | Motor rated frequency(Hz) |
| $J$ | Motor inertia (kg·m²) |
| $F$ | Motor friction coefficient |
| $p$ | Motor pole pairs |
| $S$ | Motor initial slip |
| $L_1$ | Pump outlet height(m) |
| $L_0$ | Liquid surface height(m) |
| $L_{st}$ | Height between pump outlet and liquid surface(m) |
| $R$ | Solar radiation(w/m²) |
| $t_c$ | Total numerical time(s) |
| $\epsilon_Q$ | Total uncertainty of flow(%) |
| $\epsilon_H$ | Total uncertainty of head(%) |
| $\epsilon_{QS}$ | System flow uncertainty(%) |
| $\epsilon_{QR}$ | Random flow uncertainty(%) |
| $p_1$ | Inlet pressure(Pa) |
| $p_2$ | Outlet pressure(Pa) |
| $\epsilon_{p1}$ | Measurement uncertainty of inlet gauge pressure(%) |
| $\epsilon_{p2}$ | Measurement uncertainty of outlet gauge pressure(%) |

### 1. INTRODUCTION

With the many advantages of energy saving, environmental protection, low cost and good adaptability to crops, the photovoltaic pump system is widely used in agricultural irrigation, urban waterscape and grassland animal husbandry, etc. Therefore, the optimization of photovoltaic pump system has been a research hotspot.

At present, there are many studies on optimization of photovoltaic pump system. Based on the maximum power point tracking (MPPT) and genetic algorithm, Chandel et al. (2015) and Ghoneim (2006) showed that the intensity of solar radiation is the main factor affecting the efficiency of photovoltaic pumps. Shi et al. (2016) optimized the controller of the photovoltaic pump system and the efficiency of the subsystem is improved by 10%. Chen et al. (2016) combined the motor drive with MPPT algorithm to achieve maximum power point tracking and improve the system response time. Tiwari & Kalamkar (2018) studied the water delivery characteristics of the photovoltaic pump system and the effect of solar radiation on the pump performance was also analyzed. The optimal solar radiation for this system was found to be from 400 W/m² to 800 W/m². To study the operation characteristics of the motor, Ding et al. (2016) established a motor model by MATLAB/Simulink and found that good flow rate control can improve the utilization of solar energy effectively. Gherbi et al. (2017) coupled the photovoltaic pump with the DC motor. The pump performance was improved significantly by the optimization of the pump current and voltage. Campana et al. (2013) analyzed alternating current (AC) and direct current (DC) photovoltaic pumps. The results show that the AC fixed system can improve the performance of the photovoltaic water pump system. Liu et al. (2014) studied the load matching characteristics of the photovoltaic pump system under different pump flow rates. Boutelhig et al. (2011) studied the pump efficiency, total system efficiency and economic cost of different pumps with different size photovoltaic arrays and the optimal configuration scheme was proposed. Zhu et al. (2017) studied an automatic tracking photovoltaic pump system. The system can effectively increase the water output of the system by 35% and reduce the system cost by 21%. Cong et al. (2010) improved the operation of photovoltaic pumps under weak solar radiation by experiments and simulations.

Although there are many studies on optimization of photovoltaic pump systems, most of the research focus on MPPT (Sun et al. 2013; Suo 2017; Xing 2017), motor control (Moulay-Idriss & Mohamed 2013; Mapurunga et al. 2014; Zhen & Zhen 2017) and system matching (Benghanem et al. 2013; Liu 2017; Liu et al. 2017), few attentions were paid to the photovoltaic pump performance under transient solar radiation, which is very important to the photovoltaic pump design. So Almost all the existing photovoltaic pumps are selected from the existing products, which may be not the best choice. This is because the pump is usually designed according to the fixed rotational speed and flow rate.

The inner flow determines the pump performance. With the development of CFD, numerical simulation has undoubtedly become the best tool to reveal the internal flow in pumps. AlObaidi et al. (2019) used CFD
technology to analyze the flow field in the axial flow pump and found that the pressure of the axial flow pump increased from the inlet impeller to the outside. AlObaidi (2020a, 2020b, 2020c, 2020d) and Ahmed Ramadhan (2020) used numerical methods to analyze the influence of different blade angles, the number of impellers and guide vanes on the flow characteristics. The results show that with the increase of the number of impellers and guide vanes, the pressure at the outlet area of the pump increases, the pressure distribution is better when the blade angle of 60°. At the same time, the influence of cavitation on pressure pulsation was studied and found that cavitation started at a higher design flow rate, and the collapse of cavitation bubbles would produce more pressure pulsation. However, as for the photovoltaic pumps, the transient solar radiation leads to the change of the pump rotational speed and flow rate, which makes it difficult to give boundary conditions for internal flow simulation of the photovoltaic pumps.

To solve this problem, the dynamic characteristic algorithm of the photovoltaic pump system was established by MATLAB/Simulink. Then the change rule of pump rotation speed and flow rate under transient solar radiation were respectively obtained and fitted into functions as the boundary conditions of CFD simulation. Therefore, the internal flow and pressure pulsation in the photovoltaic pump under transient solar radiation can be simulated for the first time and the results were analyzed in detail. Based on the analysis on the internal flow in the photovoltaic pump, the optimization method and design method for the photovoltaic pump can be explored, which can make the photovoltaic pump more high efficiency and stable under variation condition.

2. TEST OF SYSTEM DYNAMIC CHARACTERISTIC

In order to validate numerical simulation method, the dynamic characteristic of the pump under different solar radiations were obtained through the test.

2.1. Test rig

The test rig is shown in the Figure 1, which is composed of photovoltaic array analog power supply, inverter, pump parameter measuring instrument, pressure pulsation sensor, pressure transmitter, electromagnetic flowmeter and pump outlet control valve, etc. Table 1 shows the type and accuracy of the test equipment.

According to Table 1 and Formula 1, the total uncertainty of the test rig is 0.332%.

\[
E_n = \sqrt{E_1^2 + E_2^2 + E_3^2 + E_4^2 + E_5^2}
\]  

(1)

Figure 1 | Sketch of experiment equipment. 1. Power supply cabinet 2. Photovoltaic Array Analog Power 3. Inverter 4. Pump Parameter Measuring Instrument 5. Model Pump 6. Pressure Pulsation Sensor 7. Pressure transmitter 8. Pump outlet pipeline 9. Electromagnetic flowmeter 10. Regulating Valve 11. Pump Installation Tank 12. Circulating Water Tank 13. Water Tank Connection Valve 14. Circulating Pipeline 15. Computer.
The uncertainty of $Q$ and $H$ calculated by formulas 2 and 3 are 0.2% and 0.301%, respectively.

$$e_Q = \pm \left[ (e_{Q_0})^2 + (e_{Q_1})^2 \right]$$  \hspace{1cm} (2)$$
$$e_H = \pm \left[ \frac{P_1}{\rho gH_1}e_{p_1} + \frac{P_2}{\rho gH_2}e_{p_2} \right]$$  \hspace{1cm} (3)

To reduce random error, one parameter is measured 5 times and the least square method is applied to get the best value among the multiple observations with the same accuracy.

### 2.2. Test procedure

In the test, the photovoltaic array analog power provides to the pump through the inverter. The discharge pressure is measured by pressure transmitter and the pressure pulsation at pump outlet is obtained by the pressure pulsation sensor. The flow rate is controlled by the valve and recorded by the electromagnetic flowmeter. The pump performance is analyzed by the pump parameter measuring instrument. The test method is shown as following.

1. Open the power supply cabinet, and fully open the water tank connection valve, slowly open the regulating valve, and start the pump to run at the rated speed.
2. Adjust the regulating valve to different working conditions until the pump runs stably, then record the experimental data. Repeat step 2 to get the optimal valve opening.
3. Adjust the output power of the photovoltaic array analog power supply, wait for the pump to run stably, and record the experimental data. Repeat step 3 to get the optimal photovoltaic array capacity.
4. In view of the transient solar radiation intensity, the output power of the photovoltaic array and the pump outlet pressure pulsation under different solar radiation intensity change gradients were tested under the optimal configuration of the test system.
5. Regulate the photovoltaic inverter, repeat step 4.

During the test, repeat sampling of the same working condition data at least 5 times.

### 2.3. Model pump

The model pump is a 6-stage submersible pump and the 6 impellers are the same. The main design parameters of the pump are that flow rate $Q_d = 4$ m$^3$/h, head $H_d = 30$ m and pump efficiency $\eta_d = 40\%$. The model pump consists of impellers, guide vanes and cavity. The geometric details of the impeller are shown in the Table 2.

### 2.4. Test results

The pump dynamic characteristic under different solar radiation is shown in the Figure 2. As shown in the Figure 2, the pump flow rate and rotation speed all increase gradually with the increase of solar radiation. When the solar radiation is 1,000 W/m$^2$, the pump flow rate, head and rotation speed reach the maximum. At this time, the pump flow rate is 4.7 m$^3$/h, head is 24.9 m and rotation speed is 2,725 r/min.

### Table 1 | Type and accuracy of test equipment

| Test equipment                          | Type                          | Measuring range                                  | Accuracy  |
|----------------------------------------|-------------------------------|--------------------------------------------------|-----------|
| Photovoltaic array simulator           | Chroma 62050H-600S           | Output voltage 0 ~ 600 V, Output current 0 ~ 8.5A, Output power 0 ~ 5,000 W | ± 0.1%($E_1$) |
| MPPT controller                        | SPC-1000                     | 60V,100A                                         | ± 0.2%($E_2$) |
| Electromagnetic flowmeter              | KEF-DN50                     | 0 ~ 1 MPa                                        | ± 0.2%($E_3$) |
| Static pressure sensor                 | MIK-P300                     | 1 ~ 30 m$^3$/h                                   | ± 0.1%($E_4$) |
| Pump parameter tester                  | TPA-3A                       | -                                                | ± 0.1%($E_5$) |
3. Dynamic Characteristic Simulation of Photovoltaic Pump System

To obtain the boundary conditions for CFD, each part in the system is modeled and integrated by MATLAB/Simulink firstly. Then the dynamic characteristics of the photovoltaic pump system were obtained.

Table 2 | The impeller geometric details

| Impeller parameters             | Value |
|---------------------------------|-------|
| Blade number                    | 6     |
| Inlet diameter/mm               | 38    |
| Blade hub wrap angle/°          | 84    |
| Installation angle of blade inlet/° | 28 |
| Installation angle of blade outlet/° | 24.5 |
| Outlet width/mm                 | 6     |

Figure 2 | Pump performance under different solar radiations. (a) Flow rate and head. (b) Pump speed.
3.1. The algorithm of photovoltaic water pump system

The dynamic characteristic prediction algorithm of photovoltaic pump system was established by MATLAB/Simulink. Connect each component of the photovoltaic water pump system, namely photovoltaic panel-controller-inverter-motor-photovoltaic pump. According to formula (4), a Simulink simulation model of photovoltaic panels is established. The controller uses a simple and low-cost perturbation observation method as the MPPT algorithm. The inverter adopts space vector pulse width modulation scheme to realize variable frequency control. The motor model used is the Asynchronous Machine module that comes from Simulink software. The motor input is three-phase voltage and load torque and the output is angular velocity. The algorithm is shown in the Figure 3.

When the solar radiation intensity $G$ and temperature $T$ change, the relationship between the output voltage $U$ and current $I$ of the photovoltaic panel are below.

$$ I = I_{SC}[1 - C_1(e^{G_{DC}} - 1)] + \Delta I $$

Here,

$$ C_1 = (1 - I_m/I_{SC})e^{-\frac{G_{DC}}{C_2Uoc}}; $$
$$ C_2 = (U_m/U_{DC} - 1)/\ln (1 - I_m/I_{SC}); $$

$$ \Delta I = \alpha G\Delta T + \beta \left(\frac{G}{G_{ref}} - 1\right)I_{SC}; $$

$$ \Delta U = -\beta \Delta T - \frac{R_S}{C_1}\Delta I; $$

$$ \Delta T = T - T_{ref}. $$

3.2. Parameters in the algorithm

The parameters of the photovoltaic pump system algorithm are given as below.

Figure 3 | Simulation algorithm of photovoltaic pump system.
(1) Photovoltaic array

The photovoltaic array current temperature coefficient $\alpha = 0.4 \text{ mA/°C}$. Photovoltaic array voltage temperature coefficient $\beta = -60 \text{ mV/°C}$. The photovoltaic array resistor $R_S = 2 \Omega$. The photovoltaic array temperature $T_{ref} = 25 \text{ °C}$. The photovoltaic array solar radiation $G_{ref} = 1,000 \text{ W/m}^2$. The photovoltaic array short-circuit current $I_{SC} = 1.877 \text{ A}$. The photovoltaic array current at maximum power point $I_{m} = 1.852 \text{ A}$. The photovoltaic array open circuit voltage $U_{OC} = 580.02 \text{ V}$. The photovoltaic array voltage at maximum power point $U_{m} = 540\text{ V}$.

(2) Motor

The motor rated power $P_n = 550 \text{ W}$. The motor line voltage $V_n = 380 \text{ V}$. The motor rated frequency $f_n = 50 \text{ Hz}$. The motor inertia $J = 0.00075 \text{ kg·m}^2$. The motor friction coefficient $F = 0.005$. The motor pole pairs $p = 1$. The motor initial slip $S = 0.08204$.

(3) Pump

The pump rated rotational speed $n = 2,753 \text{ r/min}$. Fluid density $\rho = 1,000 \text{ kg/m}^3$. Liquid surface height $L_0 = 0 \text{ m}$ and pump outlet height $L_1 = 2.37 \text{ m}$. Height between pump outlet and liquid surface $L_{st} = 2.37 \text{ m}$.

(4) Solution parameters

The discrete mode is selected and $T_s = 5 \text{ e}^{-5} \text{s}$. Variable step-size and ode23t are used as solve nonlinear equations.

3.3. Validation of results

To verify the reliability of dynamic characteristic algorithm based on MATLAB/ Simulink, the results were compared with the test results. Figure 4 shows the comparison between the simulation results and test results under different solar radiations (400 W/m², 500 W/m², 600 W/m², 700 W/m², 800 W/m², 900 W/m², 1,000 W/m², 1,100 W/m² and 1,200 W/m²).

As can be seen from Figure 4, the simulation results show a good agreement with the test results and the former is a little larger than the latter. This may be because the module built by Simulink is more efficient than the corresponding equipment used in the test. With the increase of solar radiation, the pump rotation speed increases gradually. When the solar radiation reaches 1,100 W/m², the pump rotation speed gets gradually stable and the deviation between simulation and test decreases gradually. The overall deviation is less than 5%. Under higher solar radiation, the deviation even is less than 3.6%. With the increase of solar radiation intensity, the flow rate and head gradually increase also. Under steady state conditions, the relative deviation between the simulation value and the test result corresponding to the flow rate and head is also within 5%. Therefore, this dynamic characteristic algorithm can be applied in the study.

3.4. Pre-boundary condition

Figure 4 shows the pump dynamic characteristic of rotational speed and flow rate under different solar radiations. However, it cannot be directly used as the boundary conditions directly in the CFD, because the independent variable is not time. To provide the proper boundary conditions for CFD, the curves of rotational speed and flow rate under transient change of solar radiation are fitted into the function of time. The curve is obtained by dynamic algorithm.

The total calculation time $t_c$ is the time required for the model pump needs to run from transient operation to stabilize operation and $t_c$ is determined by simulation results. Using $f = 2,000 \text{ Hz}$ as sampling frequency under different solar radiations and the corresponding time step $\Delta t = t_c/f$. For example, the change curves of pump rotational speed and flow rate under the transient solar radiation from 400 W/m² to 500 W/m² are shown in the Figure 5. The results are fitted into the functions of time, the correlation coefficient of rotational speed fitting function curve is 0.989 and the correlation coefficient of flow rate fitting function curve is 0.991.

The CEL function of rotating speed fitted according to the simulation results is:

\[
- (18.45.59 + 480.71 \times (t/1[s]) - 393.69 \times ((t/1[s])^2) \\
+ 117.52 \times ((t/1[s])^3)) \text{[rev min}^{-1}])
\]
The flow rate CEL function fitted is:

\[(0.894 + 0.233\times(t/1[s]) - 0.191\times((t/1[s])^2) + 0.057\times((t/1[s])^3))\text{[kg s}^{-1}\text{]} \quad (6)\]

Finally, the rotational speed, flow rate, time step and total numerical time under different transient change of solar radiations are shown in Table 3.

4. NUMERICAL SIMULATION METHOD OF INTERNAL FLOW

In order to predict the pump performance under transient change of the solar radiation by CFD accurately, the numerical simulation method of the model pump was built.

4.1. 3D Model and grid generation

As shown in Figure 6, Creo 2.0 was used to build the 3D model of computational domain and the ICEM was used to generate grid. The calculation domain consists of inlet extension, impeller, cavity, guide vane and outlet extension. To reduce the influence of boundary conditions, the inlet extension length is 4 times the pump inlet diameter and the outlet extension length is 4 times the pump outlet diameter.

Since the model pump is a 6-stage pump, there are six groups of impeller, cavity and guide vane in calculation. Compared with tetrahedral mesh and mixed mesh, hexahedral mesh has the advantages of high precision, good

![Figure 4](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.188/902516/ws2021188.pdf)

**Figure 4** | Test and numerical simulation curves. (a) Pump rotational speed. (b) Flow rate and head.
convergence and short calculation time. Therefore, the hexahedral mesh is applied to the grid generation of impeller, cavity, inlet extension part and outlet extension part. Due to the complexity of guide vane, the tetrahedral unstructured grid is used. The grid of each part is shown in the Figure 7.

**Figure 5** | Simulation curves and fitting curves of pump rotational speed and flow rate. (a) Rotation speed. (b) Flow rate.

**Table 3** | The rotational speed and flow rate under different solar radiations

| Solar radiation (W/m²) | Rotation speed function(r/min) | Flow rate function(kg/s) | Time step .Δt(s) | Total numerical time .tc(s) |
|------------------------|--------------------------------|--------------------------|------------------|------------------------|
| 400–500                | \( n = 1,845.59 + 480.71t - 393.69t^2 + 117.52t^3 \) | \( Q = 0.894 + 0.233t - 0.191t^2 + 0.057t^3 \) | \( 7.5 \times 10^{-4} \) | 1.5 |
| 500–400                | \( n = 2,146.87 - 1,562.35t + 1,602.81t^2 - 507.1t^3 \) | \( Q = 1.05977 - 0.757t + 0.776t^2 - 0.246t^3 \) | \( 8 \times 10^{-4} \) | 1.6 |
| 600–700                | \( n = 2,264.23 + 544.23t - 560.37t^2 + 175.31t^3 \) | \( Q = 1.0966 + 0.264t - 0.271t^2 + 0.085t^3 \) | \( 6.5 \times 10^{-4} \) | 1.3 |
| 700–600                | \( n = 2,434.88 - 1,007.57t + 1,198.86t^2 - 425.17t^3 \) | \( Q = 1.179 - 0.488t + 0.581t^2 - 0.206t^3 \) | \( 7.5 \times 10^{-4} \) | 1.5 |
4.2. Grid independence check

A grid independence check, including 5 schemes, was carried out to eliminate the effects of the grid number on the calculation results. The grid independence check results are shown in the Table 4. The rated head was used as the criteria.

As shown in Table 4, when the total number of grid is less than 14.5 million, the head will increase with the increase of the total grid number. After the scheme C, the head almost keeps constant. Therefore, considering the calculation resource and time, the scheme C was selected finally.

4.3. Boundary conditions

CFX15.0 was used to conduct numerical simulation of the inner flow in the pump. The rotating domain includes 6 impellers. The others are all in the static domain. The turbulence model was SST $k$-$\omega$.

The non-slip wall surface was adopted and the roughness was set to be 0.05 mm. The inlet boundary condition was the pressure inlet and the pressure was 1 atm. The outlet boundary condition was the mass flow rate outlet. According to the Table 3, the flow rate function was used as mass flow rate outlet and the rotational speed function was applied to appoint pump rotational speed. High resolution discretization was adopted in governing equations. The advantage of the higher resolution is that the calculation accuracy is higher and the error is smaller.

The impeller interface was set as frozen rotor interface for steady flow calculation. And the impeller interface was set as transient stator-rotor interface for the unsteady flow calculation. The rest interfaces were set as static-static interface. To ensure the convergence and accuracy of fluid calculation in each time step, the steady simulation result was used as the initial condition for the unsteady flow simulation and 50 iterations were performed in each time step.

4.4. Validation of numerical method

The pressure pulsation at pump outlet between the numerical simulation and the test is compared under solar radiation transient change of 600 W/m²–700 W/m² and 700 W/m²–600 W/m².

Figure 8 shows pressure pulsation at pump outlet under solar radiation transient change of 600 W/m²–700 W/m² and 700 W/m²–600 W/m². It can be seen from the Figure 8 that the pressure at pump outlet changes significantly with the transient change of solar radiation. When the solar radiation increases transiently, the pressure at
pump outlet rises sharply and fluctuates near 200 kPa. When the solar radiation decreases transiently, the pressure decreases obviously and gets stable at about 165 kPa.

Quantitative analysis shows that the simulation relative deviation under the solar radiation transient change of 600 W/m²–700 W/m² is between 1.58% and 1.67%. The simulation relative deviation under the solar radiation transient change of 600 W/m²–700 W/m² is between 0.93% and 1.78%. Generally, the simulation result is basically the same as the test result and the deviation between the simulation result and the test result is less than 2%.

Figure 7 | Grid of photovoltaic pump. (a) impeller. (b) guide vane. (c) cavity. (d) inlet and outlet extension.
Therefore, this numerical calculation method can be used to study the internal flow in the photovoltaic pump under transient change of solar radiation.

5. NUMERICAL CALCULATION RESULTS AND ANALYSIS

The internal flow in the photovoltaic pump under the transient solar radiation change was simulated and analyzed in detail.

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**Table 4 | Grid independence check**

| Scheme | Grid size/mm | Grid number | Head H/m | Number of iterations |
|--------|--------------|-------------|----------|---------------------|
| A      | 1.5          | 4.5million  | 25.83    | 2,000               |
| B      | 1.2          | 8.5million  | 25.94    | 3,000               |
| C      | 1.0          | 14.5million | 26.32    | 4,000               |
| D      | 0.9          | 22.4million | 26.33    | 5,000               |
| E      | 0.8          | 28.3million | 26.33    | 6,000               |

**Figure 8 | Pressure pulsation at pump outlet.**

(a) 600 W/m²–700 W/m². (b) 700 W/m²–600 W/m².
5.1. Static pressure in first stage impeller

Due to that the 6 impellers are the same, so only the flow in the first stage of the impeller is analyzed here. Two typical solar radiation change schemes are considered, namely 400 W/m²–500 W/m² and 500 W/m²–400 W/m². Meanwhile, the total calculation time is \( t_c = 1.5 \) s and \( t_c = 1.6 \) s, respectively.

Figure 9 shows the static pressure distribution in the middle section of the first impeller stage. As shown in Figure 9(a), the static pressure increases evidently with the increase of the solar radiation. When the solar radiation increases transiently, the static pressure at the impeller outlet increases obviously and the flow gets steady after \( t = 1.0t_c \). With the increase of the solar radiation, the low pressure area at the impeller inlet becomes larger. This may be due to that pump rotational speed increases rapidly with solar radiation sharply increasing in a short time, which makes the flow at the impeller inlet disorder. With the transient increase of the solar radiation, the pressure at the outlet of the impeller increased by 8 kPa.

Figure 9(b) shows that when the solar radiation decreases transiently, the static pressure at the impeller outlet decreases obviously after \( t = 0.5t_c \). Compared with the transient increase of solar radiation, the pressure gradient in impeller gets smaller under the transient decrease of solar radiation and the low pressure area at the impeller inlet becomes smaller. With the transient decrease of the solar radiation, the pressure at the impeller outlet decreases by 10 kPa. Under the transient change of solar radiation condition, the pressure change amplitude in impeller is gradually increased from the impeller inlet to the impeller outlet.

When the solar radiation decreases transiently, the pressure in the impeller takes longer to be stable. This may be due to the MPPT controller receives more oscillation with the transient decrease of solar radiation and it needs more time to make judgments and adjustments. The transient change of the solar radiation has more effects on the pressure at impeller outlet.

5.2. Relative velocity and streamline in the pump

Figure 10 shows the relative velocity and streamlines in the middle section of the first impeller stage under solar radiation transient increase from 400 W/m² to 500 W/m².

As shown in Figure 10, the relative velocity of the fluid near the blade pressure side is lower than that near the blade suction side, especially at the inlet of the impeller. When the solar radiation increases instantaneously, the...
fluid velocity in the impeller increases continuously. This is mainly because the rotational speed increases with the increase of solar radiation.

With the transient increase of the solar radiation, the high velocity area near the blade suction side becomes larger. Meanwhile, this high velocity area gradually expands to the blade outlet.

With the transient increase of the solar radiation, the jet-wake at the outlet of the impeller becomes more obvious. This may be due to the acceleration process of fluid near the suction side of the impeller lags behind that of fluid near the pressure side of the impeller with the increase of solar radiation.

5.3. Pressure pulsation in the pump

To study the pressure pulsation in the model pump under the transient change of solar radiation, six monitoring points were arranged in the first pump stage of the impeller and guide vanes. The monitoring points are shown in Figure 11.

Figure 12 is the pressure pulsation in time domain at 6 monitoring points. As can be seen from Figure 12(a), when the solar radiation increases transiently, the pressure pulsation at the impeller inlet (monitoring points 1) decreases a little, while the pressure pulsation at the other monitoring points all increase. Meanwhile, the pressure pulsation at the impeller inlet (monitoring points 1) is the maximum. This is because the transient increase of solar radiation causes the motor speed increases sharply and the fluid velocity at the impeller inlet becomes faster, resulting in the pressure at the impeller inlet has the maximum pulsation.

With the increase of solar radiation, the pressure pulsation in the impeller increases. The pressure pulsation at impeller outlet (monitoring points 3) is higher than that at the middle of the impeller (monitoring points 2). This is because the pressure increases with the impeller radius under the same rotational speed and flow rate and the radius of monitoring points 3 is larger than that of the monitoring points 2. The pressure from the impeller outlet to the guide vane outlet becomes stable at 123 kPa. The pressure in the impeller changes greatly before 0.6 s and then stabilizes gradually.

As can be seen from Figure 12(b), when the solar radiation decreases transiently, the pressure pulsation at impeller inlet (monitoring points 1) increases a little, while the pressure pulsation at the other monitoring points all decrease, which is contrary to that under the transient increase of solar radiation. Compared to the pressure pulsation at other monitoring points, the pressure from the impeller outlet to the guide vane inlet

Figure 10 | Relative velocity and streamline in the first stage impeller. (1) t = 0, (2) t = 0.5t_c, (3) t = t_c.

Figure 11 | Pressure pulsation monitoring points.
(monitoring points 3, 4 and 5) are more affected by the transient decrease of the solar radiation. The pressure pulsation difference at monitoring point 5 is the maximum and it is about 10 kPa.

The pressure in the impeller needs more 0.2 s to get stable when the solar radiation decreases transiently. Moreover, the pressure pulsation from the impeller outlet to the guide vane inlet shows small fluctuation amplitude and large downtrend. This may be due to the rapid decline of pump rotational speed when the solar radiation decreases transiently. Although it has little effect on the pump flow rate, it makes the flow rate in the pump become unsteady. Also, it can be seen from the time-domain diagram that the pressure pulsation under transient conditions has no periodicity, which is similar to the results that obtained by AlObaidi (2020a, 2020b, 2020c, 2020d).

6. CONCLUSIONS

In this paper, each part of the photovoltaic pump system was modeled and integrated by MATLAB/Simulink firstly and the change rule of pump rotational speed and flow rate under different solar radiations was obtained. Then the results of the change rule were fitted into functions of time as the boundary conditions for internal flow simulation of photovoltaic pump. This is the first time that CFD has been used to simulate and analyze the internal flow of photovoltaic pumps under the transient changes of solar radiation. The main conclusions are below.

1. As for pressure pulsation at the pump outlet, the relative deviation between the simulation results and the test results under different solar radiation intensity transients are all within 2%. The numerical simulation method for photovoltaic pumps in this paper is highly reliable.
2. When the solar radiation increases transiently, the static pressure in the impeller increases obviously and the low pressure area at the impeller inlet becomes larger. The high velocity area near the blade suction side becomes larger and the jet-wake at outlet of the impeller becomes more obvious.
3. With the increase of solar radiation, the pressure pulsation in impeller increases except the pressure at impeller inlet. The transient change of the solar radiation has more effects on the pressure at the impeller outlet and less effect on pressure at the impeller inlet.
4. The transient decrease of solar radiation has more effects on the pressure pulsation from impeller outlet to the guide vane inlet. The maximum differential pressure is 10 kPa at monitoring point 5. The pressure in the impeller needs to exceed 0.2 s to become stable.
The intensity of solar radiation is only one of the factors that affect the operation of photovoltaic pumps. It is necessary to further study the effect of the comprehensive effects of various factors on the performance of the system. Also, in the future, based on the internal flow simulation, the effect of flow induced force on the photovoltaic pump structure will be considered by fluid-structure interaction under transient solar radiation, which can improve the design of the photovoltaic pump.

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DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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