Evaluation of Photovoltaic Pumped Hydroelectric Storage System using a Computational Approach

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***Abstract*— In this study, evaluation of Photovoltaic Pumped Hydroelectric Storage (PHES) system modelled using SolidWorks CAD simulation software is presented. The essence of the evaluation is to ensure that the modelled PHES system behavior is in consonance with the relevant laws governing the principles of operations of fluid flows. As such, the evaluation focused on the system pressure variation, system flow duration and the theoretical power expectations for the photovoltaic pumped hydroelectric storage. For the system pressure profile, the slice interval of approximately 0.28 m allowed for a smooth gradient, and the reduction in pressure from approximately 171.07 kPa at the top to 147.15 kPa at the bottom which confirms the accuracy of tank geometry, equation model and fluid density inputs. For the flow duration analysis, the flow values ranged from approximately 0.00087775 m³/s at the highest level to 0.00087260 m³/s at the lowest. During the simulation in SolidWorks CAD software, relevant data for the evaluation were collected. Furthermore, for the theoretical power expectations analysis, the results showed that the highest power input (150.15 W) corresponded with the topmost slice, while the lowest power input (128.40 W) was associated with the last slice. In all, the results showed that the pressure distribution across the water tank slices followed a hydrostatic pattern, confirming the accuracy of fluid modeling and validating the system's layered approach to energy release. Also, the flow duration remained nearly constant across tank slices due to calibrated valve and nozzle configurations, supporting consistent energy delivery to the turbine.**

Keywords — Photovoltaic System, Solidworks CAD Simulation Software, Hydroelectric, System Pressure Profile, System Flow Duration , Theoretical Power Expectations

1. Introduction

In Nigeria, there is generally growing quest for more renewable energy systems that can be used for medium to high capacity loads, power systems that be used to power medium to large scale industries [1,2,3]. This is particularly necessary given the drastic rise in the unit cost of energy for Band A which most industries across Nigeria require [4,5,6]. Accordingly, many researchers across Nigeria are modelling and building different kinds of hydro power plants or hybrid versions requiring solar and hydro combination [7,8,9].

One major drawback of the solar power is its stochastic nature [10,11]. As such, application of solar power in the hydropower system design brings up some design challenges. Most solar hydro power design will rarely on the solar system to pump the water which drives the hydro turbine [12,13]. However, the variable nature of the solar radiations affect the theoretical power expectations, pressure variation and flow duration of the hydro turbine [14,15,16]. As such, proper study of these parameters are essential in the design of solar hydro power plant. This issue are addressed in this study. Requisite simulation software is employed to model the solar hydro power plant and the listed parameters are well studied using different simulations runs and analyzing the simulation results obtained. The study therefore will help provide the designer to understand dynamics of the solar hydro power plant and determine the actual power generated under the varying conditions of the system.

2. Methodology

This study focus is on the evaluation of Photovoltaic Pumped Hydroelectric Storage (PHES) system designed and modelled using SolidWorks CAD simulation software. The evaluation focused on the system pressure variation, system flow duration and theoretical power expectations for the photovoltaic pumped hydroelectric storage. The PHES is designed based on the following criteria:

i. **Affordability**: The Pumped Hydro Energy Storage (PHES) system should be cost-effective and within the financial capacity of the target users.

ii. **Performance**: The turbine must operate efficiently according to specified design requirements.

iii. **Power Generation**: The turbine should be capable of generating the required electrical output.

iv. **Material Availability**: The turbine should be constructed using locally and readily available materials to reduce costs and ease maintenance.

v. **Capacity**: The turbine's power output should be sufficient to meet the energy demands of the consumers, significantly exceeding what battery based photovoltaic system can provide.

The Photovoltaic Pumped Hydroelectric Storage (PHES) system CAD modelling was aimed to accurately reflect the physical dimensions and system specifications calculated through engineering analysis. The following steps were adopted for the modelling using SolidWorks CAD software;

Turn the tool on and prep

i. **Bring up the add-in library:** Select Tools → The Select Add-Ins… → then Select SOLIDWORKS Flow Simulation (check both columns).

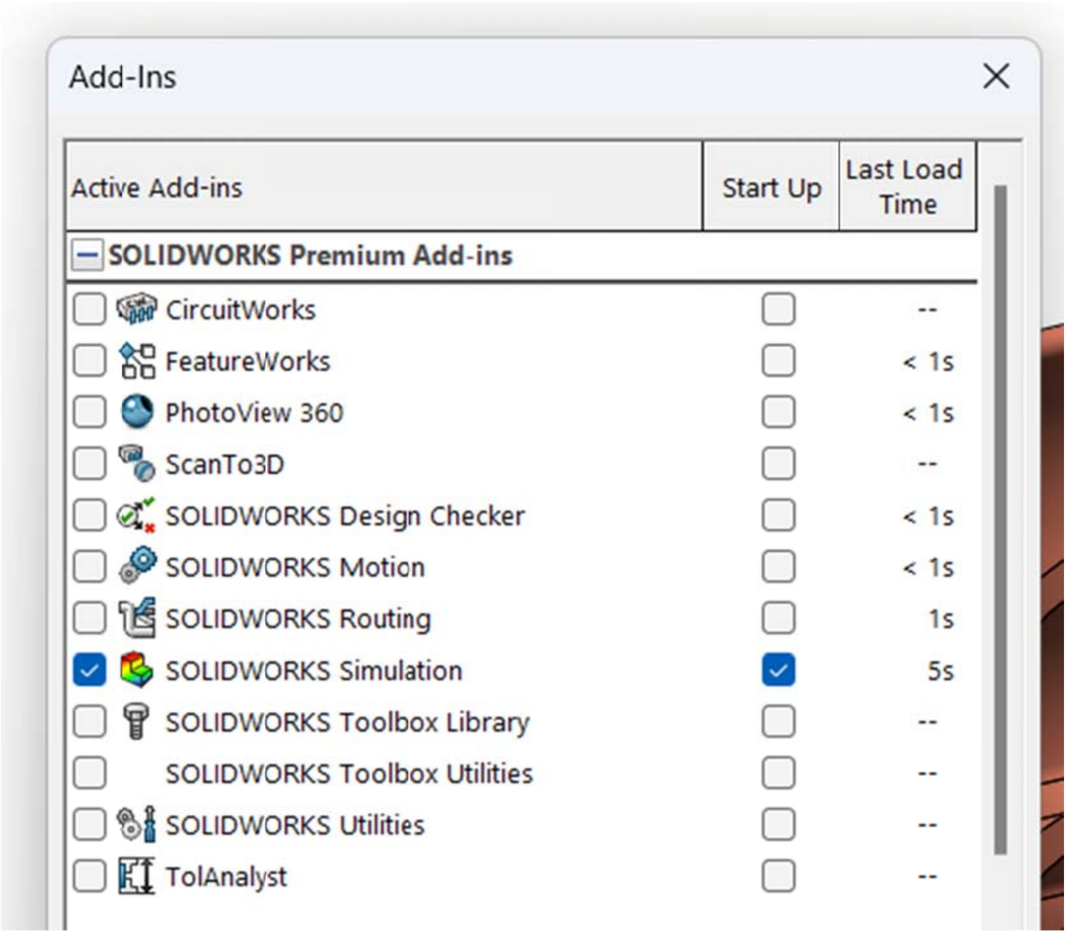

Figure 1: Enabling Add-ins for SOLIDWORKS CFD Simulation.

ii. **Clean geometry:** close tiny gaps, suppress microscopic fillets/holes that don't matter, set materials on all solids.

iii. **Orient the model:** make sure the wheel's axis is along a main axis (e.g., Z) and you know the upstream/downstream directions.

A) START A NEW PROJECT (WIZARD)

Flow Simulation → Project → Wizard…

i. **Unit system:** SI (m, s, kg, Pa).

ii. **Analysis type:**

  i. **External** (typical for water flowing around a wheel).

  ii. Check **Time-dependent** if you want transient history.

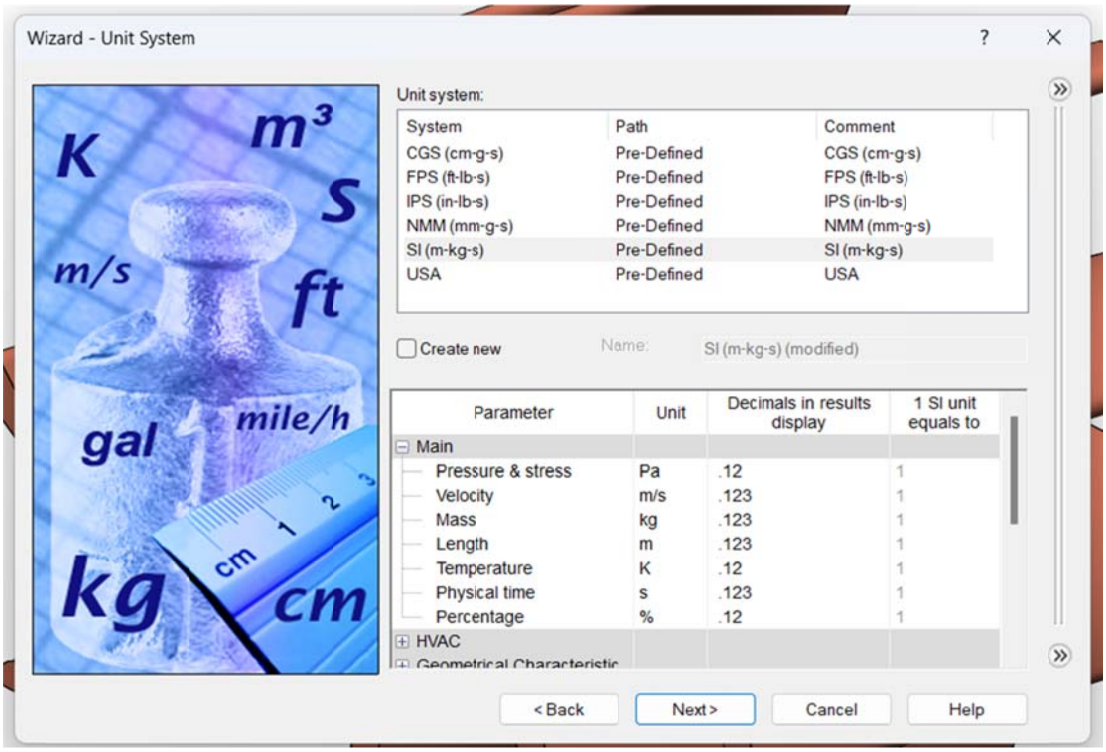

Figure 2: Selecting Units System for SOLIDWORKS CFD Simulation.

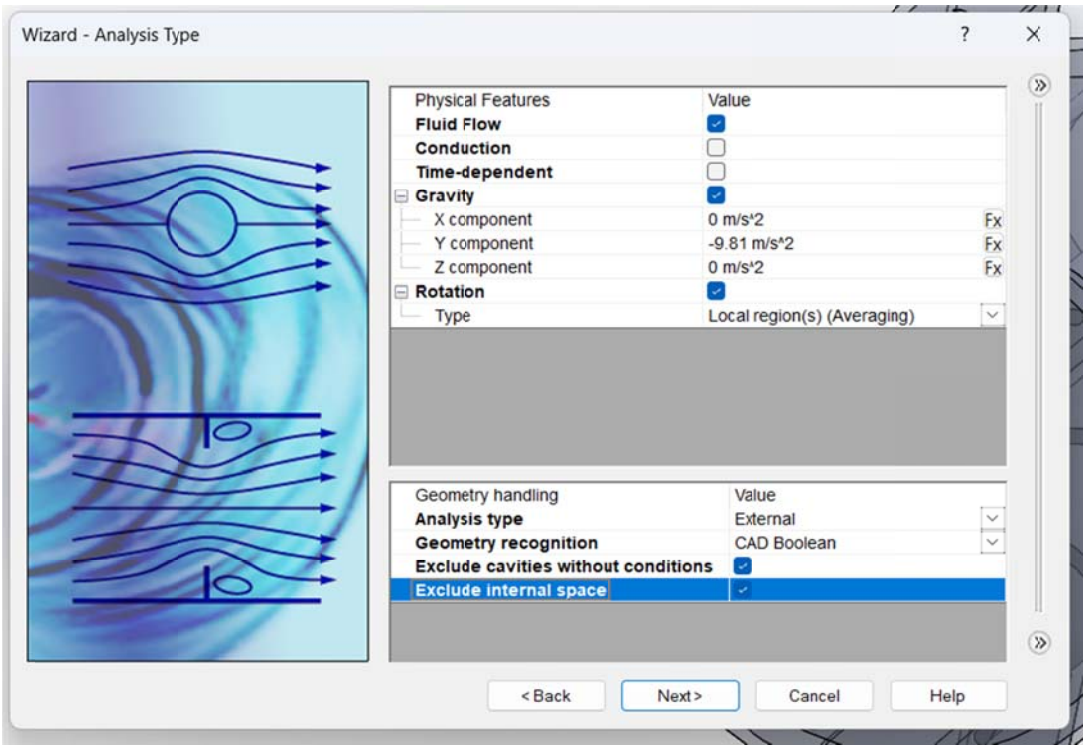

Figure 3: Input Parameters Configuration

iii. **Physical features: Gravity** → on (–Y axis).

iv. **Fluids: Single-phase (simpler):** add **Water** only.

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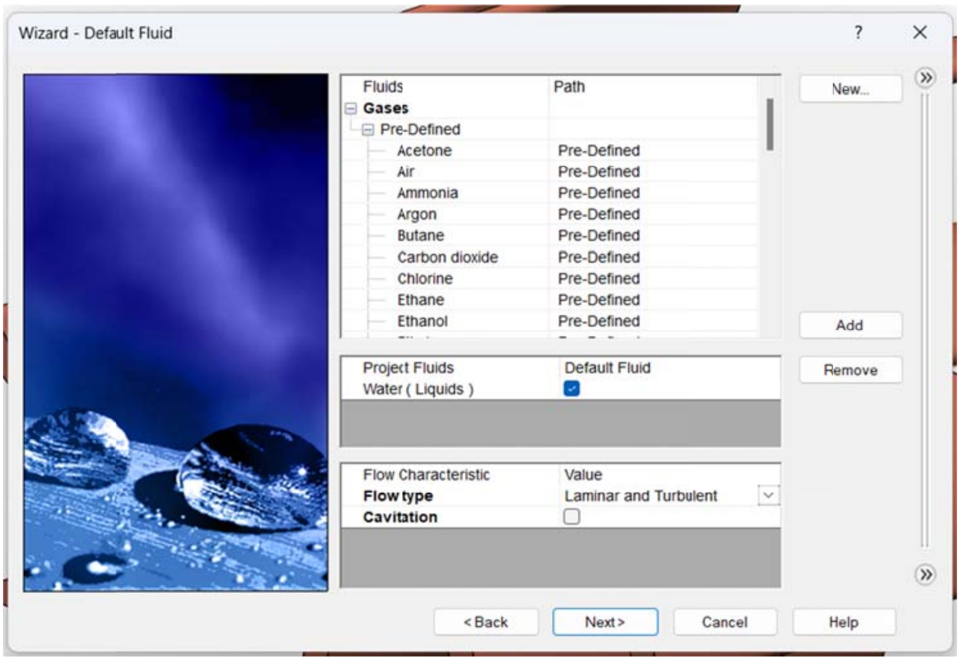

Figure 4: The flow environment Configuration

v. **Wall condition:** default No slip

vi. **Initial conditions:** At defaults (0 m/s)

vii. **Computational domain**: size the bounding box:

Finish the wizard.

B) Rotating Wheel Multiple Reference Frame (MRF)

The spinning is modeled using a **Rotating Region** (Multiple Reference Frame).

i. **Create a cylinder** (or block) that fully encloses the blades and hub with a little clearance.

ii. **Flow Simulation** → Insert → Rotating Region → pick that volume.

iii. Set **Axis** and **Speed** (20rpm).

iv. Ensure the **blades + hub** are inside the rotating region.

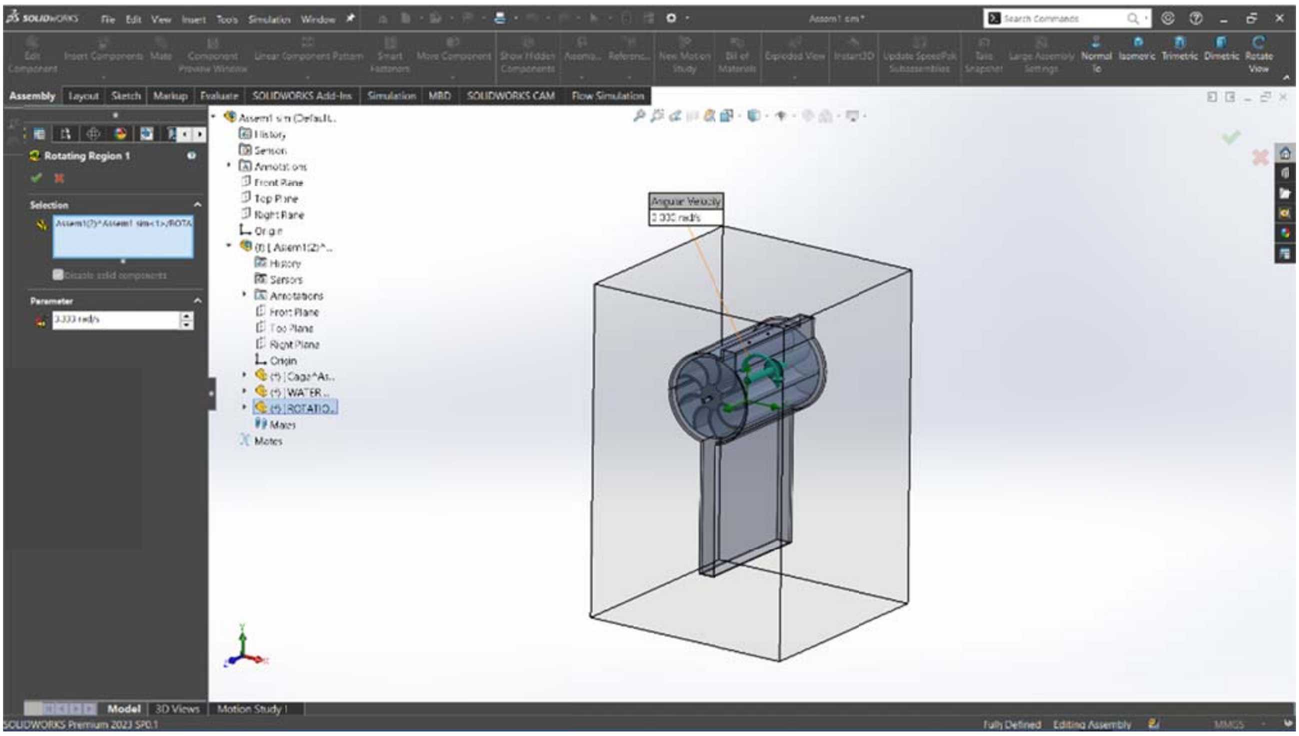

Figure 5: Rotational Region Modelling

C) Boundaries

Flow Simulation → Insert → Boundary Condition

Single-phase (submerged) setup

i. **Inlet: → inlet Pressure** (171.07 kPa).

ii. **Outlet: → Environment Pressure**.

Free-surface setup (air + water)

i. Make sure **Gravity** is on (crucial).

ii. **Inlet:** specify **volume flow rate** (water 0.00087775 m^3/s) or **velocity**; set **fluid = water**.

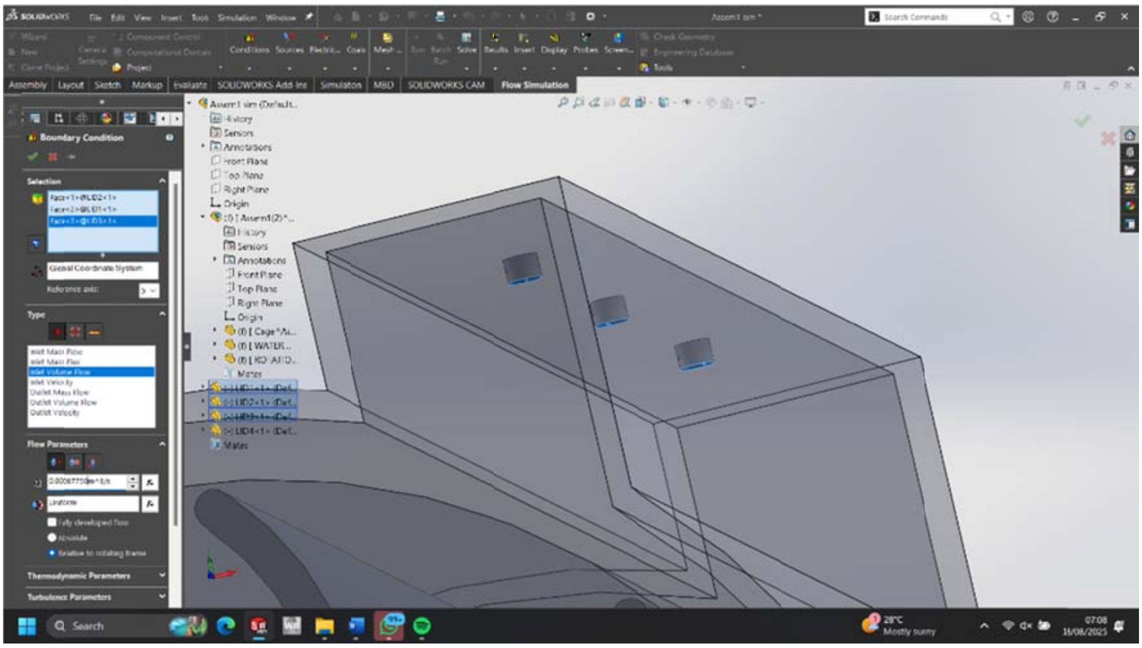

Figure.6: Setting Inlet Flow Boundaries for SOLIDWORKS CFD Simulation.

iii. **Outlet: Environment Pressure** open to air.

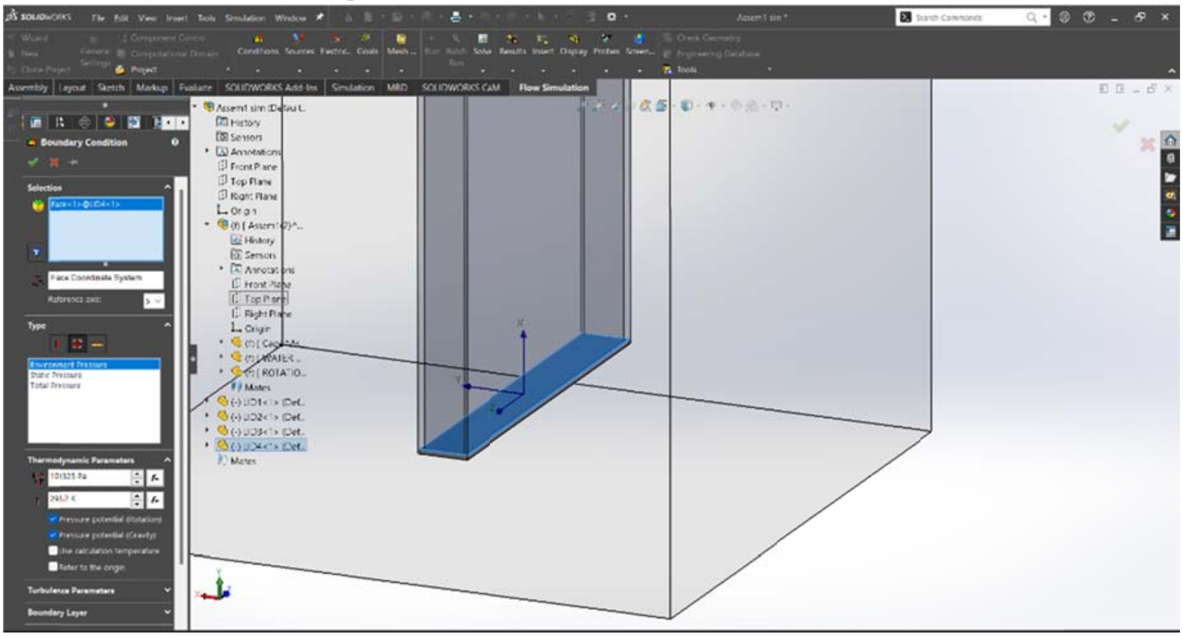

Figure.7: The Outlet Flow Boundaries Setting

D) Goals (what to monitor and converge)

Flow Simulation → Insert → Goal

i. **Surface goals** on the blades: Ave Pressure, Max Pressure, Min Pressure, Force (X/Y/Z), and Moment about the axis (this gives torque).

ii. **Global goals:** Mass flow rate, Average outlet velocity, Total pressure drop.

iii. These help convergence and let you do mesh refinement automatically.

E) Mesh

Flow Simulation → Mesh → Global Mesh…

i. Start with **Level 7**.

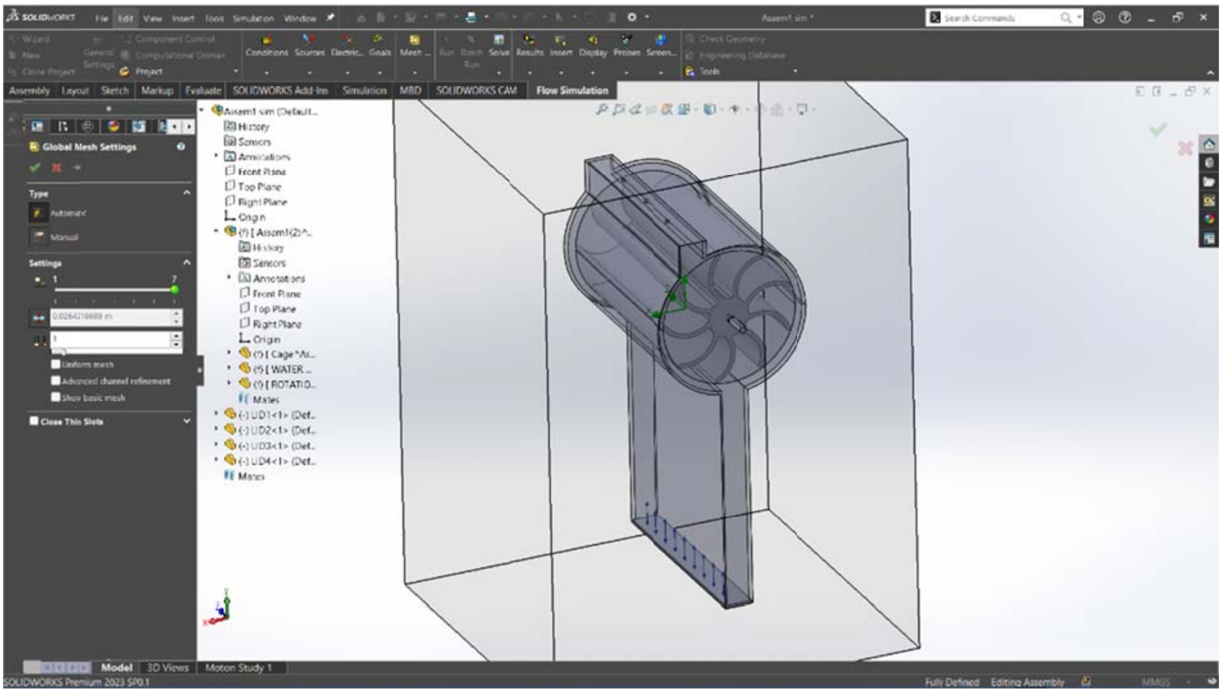

Figure 8: The Flow Mesh Setting

F) Solver settings and run

Flow Simulation → Run

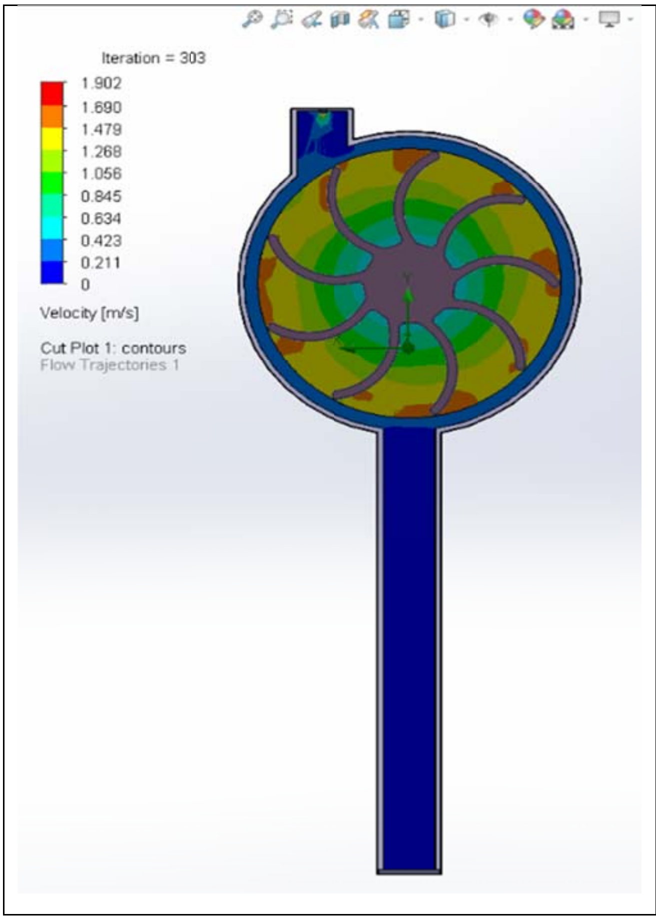

Figure 9: Flow Velocity Solver Output CFD Simulation.

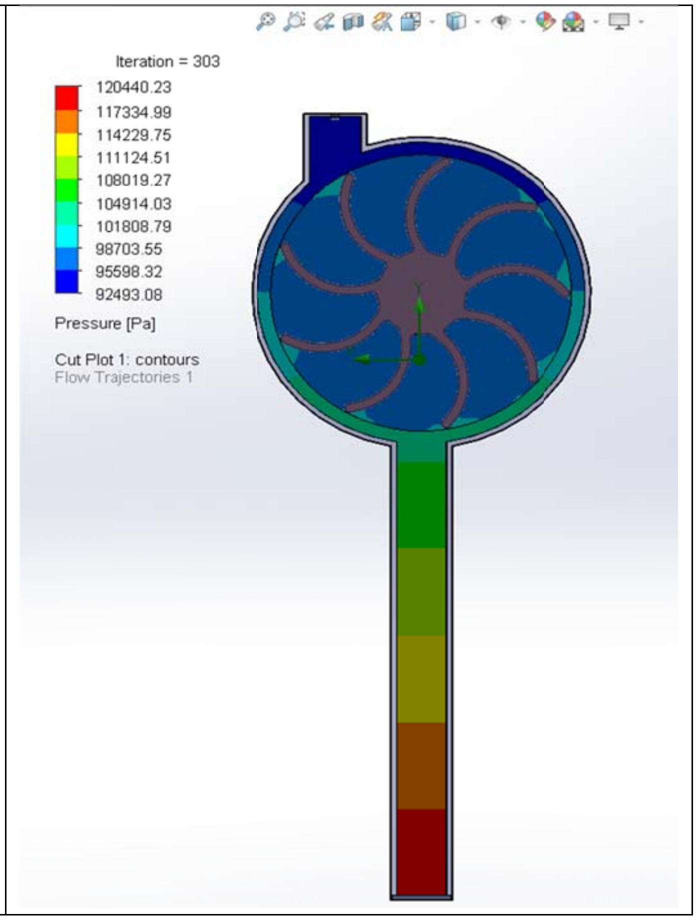

Figure 10: Flow Pressure Solver Output CFD Simulation.

G) Post-processing (pressure and velocity visuals)

Use Flow Simulation → Results:

i. **Cut Plot:** plane slices colored by **Velocity** and **Pressure**
ii. **Surface Plot:** color the blade faces by pressure or wall shear.
iii. **Flow Trajectories:** seed lines upstream; color by velocity or pressure.
iv. **XY Plots:** sample pressure/velocity along lines.
v. **Report/Animation:** Results → Animator to create videos; Results → Insert → Report for an automatic summary.

3. Results and discussion

3.1 Results for the SOLIDWORKS CAD modelling of the PHES system

The input parameters used for the SOLIDWORKS CAD modelling and simulation of the Photovoltaic Pumped Hydroelectric Storage (PHES) system is presented in Table 1 and Table 2 while the CAD model of the PHES system is presented in Figure 10.

Table 1: Input parameters for SOLIDWORKS CAD/Simulation

S/N	Parameter name	Symbol	Unit	Value or range of values used
1	Gravity acceleration	g	m/s^2	9.81
2	Fluid	–	–	Water (single-phase)
3	Wall condition	–	–	No slip
4	Initial velocity	u_0	m/s	0
5	Rotating region speed	n	rpm	20
6	Inlet pressure (submerged)	p_in	kPa	171.07
7	Outlet pressure	p_out	kPa	Environment (≈101.3 kPa)
8	Inlet volume flow rate (free-surface)	Q	m^3/s	0.00087775
9	Computational domain size	–	–	Bounding box (user-defined)
10	Mesh level	–	–	Global mesh level 7

Table 2: Some other design parameters used in the SOLIDWORKS CAD/Simulation

S/N	Parameter name	Symbol	Unit	Value
1	Rated Power of the Photovoltaic Solar Modules (Panels)	P	kW	1.35
2	Rated Power of the Synchronous Generator	P	kW	2.0
3	Rated Power of the Turbine Generator	P	kW	1.8
4	Gear Ratio	-	-	1:50
5	Rotational speed of Turbine	n	rpm	20
6	Rotational speed of Generator	n	rpm	500
7	Inlet pressure (submerged)	p_in	kPa	171.07
8	Outlet pressure	p_out	kPa	Environment (≈101.3 kPa)
9	Inlet volume flow rate (at slice 0)	Q	m^3/s	0.00087775
10	Rated Power 96V DC submersible Pump	P	kW	0.75

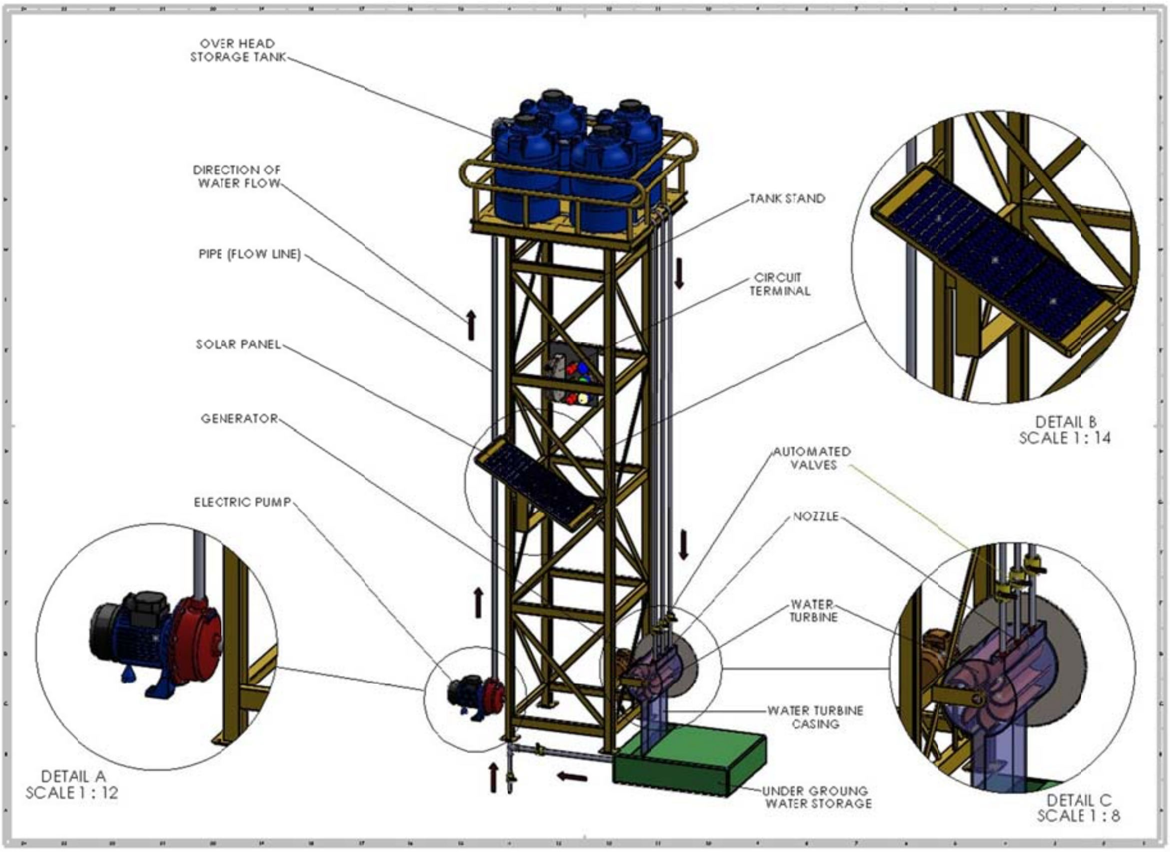

Figure 10: The CAD System Model of the Photovoltaic Pumped Hydroelectric Storage (PHES) system

3.2 Results for the PHES System Pressure Tabulations

After the SOLIDWORKS CAD modelling of the PHES system, simulations were conducted for the evaluation of the PHES system with focus on the system pressure variation, system flow duration and theoretical power expectations for the photovoltaic pumped hydroelectric storage. The results for the pressure variation at ten sections of the water tank are presented in Table 3 and Figure 11. Each section of the tank is evenly divided into slices.

Table 3 The Calculated Pressure Distribution of the System

Slice	Height (m)	Pressure (Pa)	Pressure (kPa)	Pressure (Bar)
0	17.4380	171066.8	171.0668	1.710668
1	17.1942	168675.1	168.6751	1.686751
2	16.9504	166283.4	166.2834	1.662834
3	16.7066	163891.7	163.8917	1.638917
4	16.4628	161500.1	161.5001	1.615001
5	16.2190	159108.4	159.1084	1.591084
6	15.9752	156716.7	156.7167	1.567167
7	15.7314	154325.0	154.3250	1.543250
8	15.4876	151933.4	151.9334	1.519334
9	15.2438	149541.7	149.5417	1.495417
10	15.0000	147150.0	147.150	1.471500

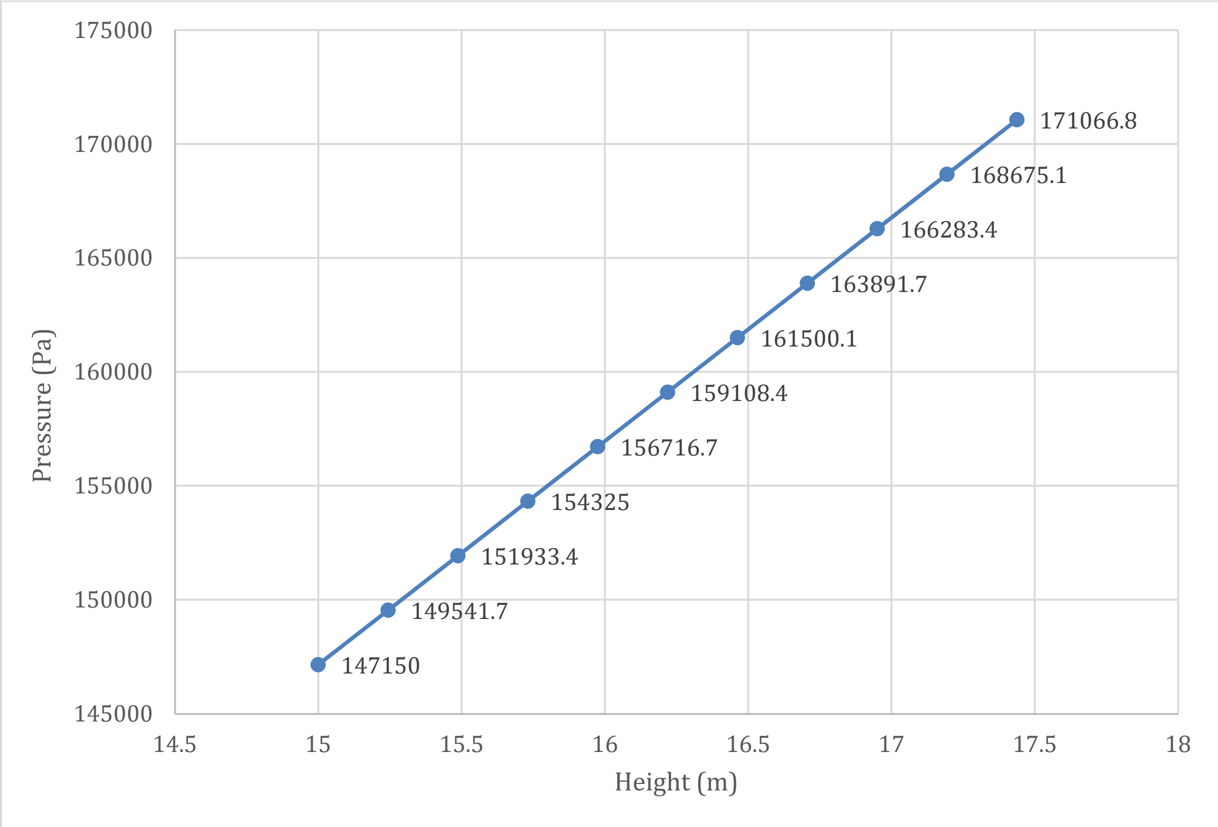

Figure 11 The graph for the pressure variation at ten sections of the water tank

As presented in Table 3 and Figure 11, the pressure distribution across the ten slices of the water tank showed a consistent downward trend. The topmost slice (0) recorded the highest pressure value, while the bottom slice (10) had the lowest. This trend is consistent with the hydrostatic law, which states that pressure in a fluid increases with depth due to gravitational force acting on the fluid column above. The slice interval of approximately 0.28 m allowed for a smooth gradient, and the reduction in pressure from approximately 171.07 kPa at the top to 147.15 kPa at the bottom confirms the accuracy of tank geometry, equation model and fluid density inputs. This pressure profile provides the fundamental basis for subsequent flow and power analysis since it dictates the available energy head within the system.

3.3 Results for the PHES System Flow Duration Curve

The graph for the PHES system flow duration curve is presented in Figure 12. It shows the flow duration curve as water flows through a one-inch PVC pipe discharging onto the turbine. Each section is evenly divided into slices, with varying flow rates ranging from 0.00087775 to 0.00087260 m^3/s. The flow rates were determined based on the pressure, pipe diameter and cumulative height for each slice using the Copely online calculator.

As seen in Figure 12, the flow duration curve of the system revealed a slightly decreasing flow rate trend as the water level in the tank declined. Flow values ranged from approximately 0.00087775 m^3/s at the highest level to 0.00087260 m^3/s at the lowest. This marginal decline in flow is attributed to the reduction in gravitational head, which in turn affects the pressure acting at the discharge orifice of the PVC pipe. The curve displayed a flattened profile, which suggests that the system is well-regulated and subject to minimal turbulence or flow shock. Since this flow profile is directly linked to turbine performance, its consistency across slices is a positive indication of energy yield predictability, especially when evaluating off-grid or rural applications of photovoltaic pumped hydro storage systems.

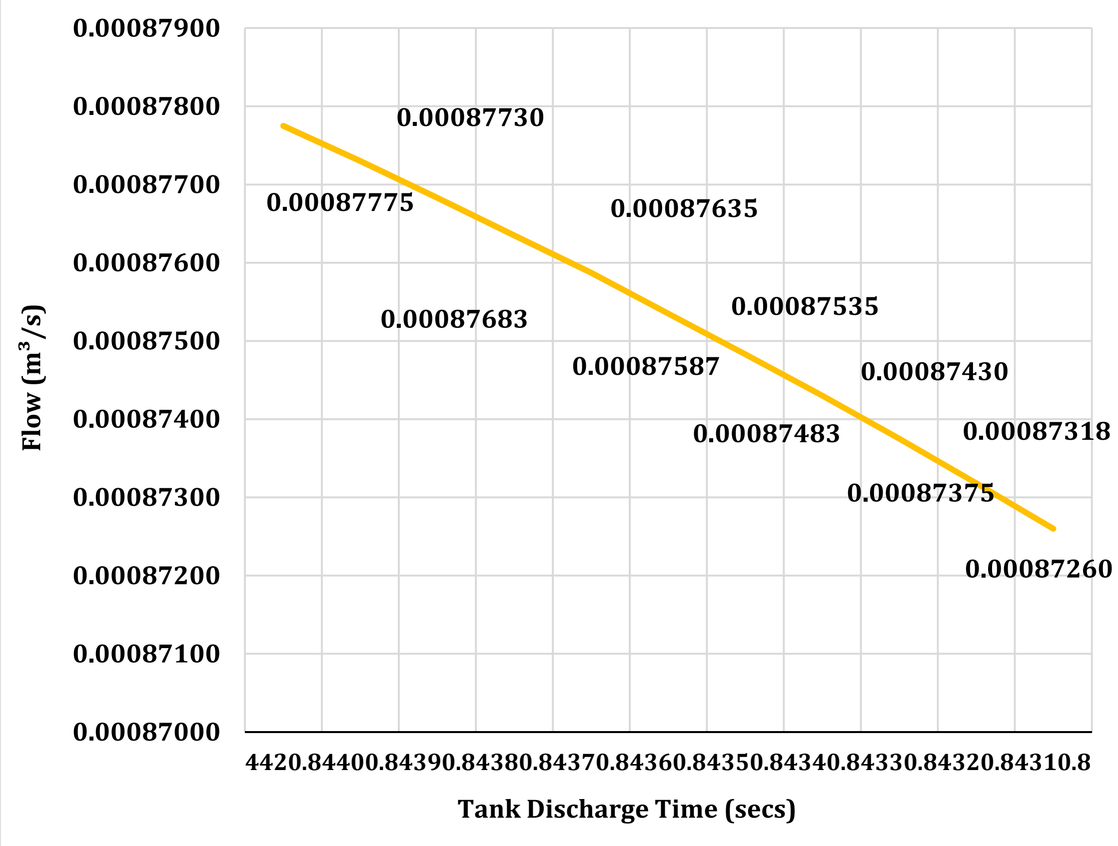

Figure 12 The graph for the PHES system flow duration curve

3.4 The Results for the PHES Theoretical Power Output

The theoretical power expectations for Photovoltaic Pumped Hydroelectric Storage using turbines 1–6, based on the following parameters: Slice Serial Number, Height (m), Flow Rate (m³/s), Slice Height (m), Power Input (W), Power Output (W), Controlled Power Output (W), Operating Time (s), Rotational Speed (rad/s), Tank Discharge Time (s), and Tank Recharge Time (s) are presented in Table 4, Table 5 and Table 6. During the simulation, the tank was divided into sections for analytical purposes. The flow rate for each slice was determined using pressure, cumulative height, and pipe diameter via the Copely online calculator. The pressure and power input to the turbine were computed. The controlled power output for turbines 1–6 was derived from the design manual by Ovens (1975). The operating time used in each of the slices is obtained by summing the discharge time of the tank and the recharge time of the tank (both expressed in seconds). The discharge time was calculated, as well as the recharge time.

Table 4. Theoretical PHES Power Results (Part 1)

Slice	Height (m)	Flow (m³/s)	Slice Height (m)	Power input (W)
0	17.438	0.00088	0.2438	150.15
1	17.1942	0.00088	0.2438	147.98
2	16.9504	0.00088	0.2438	145.8
3	16.7066	0.00088	0.2438	143.63
4	16.4628	0.00088	0.2438	141.45
5	16.219	0.00088	0.2438	139.28
6	15.9752	0.00087	0.2438	137.1
7	15.7314	0.00087	0.2438	134.1.93
8	15.4876	0.00087	0.2438	132.75
9	15.2438	0.00087	0.2438	130.58
10	15	0.00087	0.2438	128.4
TOTAL			2.438	-

Table 5: Theoretical PHES Power (Part 2)

Power Output (W)	Operating Time (secs)	Rotational Speed (rad/s)	Tank Discharge Time (secs)	Tank Recharge Time (secs)
1800	5596.8	20.94	4420.8	1176
1770	5536.8	17.94	4390.8	1146
1740	5516.8	16.94	4380.8	1136
1710	5496.8	15.94	4370.8	1126
1680	5476.8	14.1.94	4360.8	1116
1650	5456.8	13.94	4350.8	1106
1620	5436.8	12.94	4340.8	1096
1590	5416.8	11.94	4330.8	1086
1560	5396.8	10.94	4320.8	1076
1530	5376.8	9.94	4310.8	1066
1500	5356.8	8.94	4300.8	1056
-	55968	-	44208	11760

Table 6 Theoretical PHES Power (Part 3)

Controlled Power Output (W)					
Turbine 1	**Turbine 2**	**Turbine 3**	**Turbine 4**	**Turbine 5**	**Turbine 6**
200	300	600	1200	1500	300
190	290	590	1190	1470	290
180	280	580	1180	1440	280
170	270	570	1170	1410	270
160	260	560	1160	1380	260
150	250	550	1150	1350	250
140	240	540	1140	1320	240
130	230	530	1130	1290	230
120	230	520	1120	1260	220
110	210	510	1110	1230	210
100	200	500	1100	1200	200

As reported in Table 4, Table 5 and Table 6, the theoretical power output values for the ten water slices showed a direct correlation with the available hydraulic head. The highest power input (150.15 W) corresponded with the topmost slice, while the lowest power input (128.40 W) was associated with the last slice. This behavior follows the theoretical power equation for hydro systems, which multiplies gravitational head, flow rate, and water density. Six turbine models were analyzed with varying control schemes, producing outputs between 200 W and 1500 W across slices, depending on the turbine design. Notably, Turbine 6 consistently yielded the highest controlled power output, confirming its superior performance characteristics under similar operating conditions. The rotational speed of the turbines also declined steadily, showing the influence of diminishing hydraulic energy. This theoretical output assessment affirms the viability of modular hydroelectric generation from stratified water tanks when powered by solar-pumped input.

4. Conclusion

An evaluation of some key parameters that are used to ascertain the performance and reliability of photovoltaic pumped hydroelectric storage (PHES) system is presented. The PHES system is modeled using SolidWorks CAD simulation software. During the simulation relevant data for the evaluation were collected and the parameters considered in the evaluation include; system pressure profile, system flow duration and theoretical power expectations for the PHES system. The results obtained showed that the modelled PHES system behavior is in consonance with the relevant laws governing the principles of operations of fluid flows.

In all, the results showed that the pressure distribution across the water tank slices followed a hydrostatic pattern, confirming the accuracy of fluid modeling and validating the system's layered approach to energy release. Also, the flow duration remained nearly constant across tank slices due to calibrated valve and nozzle configurations, supporting consistent energy delivery to the turbine.

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