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Solution of a kind of negative flow in a Pelton turbine

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Abstract. Pelton turbine is often used where water head is extremely high. Efficiency is an important target of a Pelton turbine during the turbine designing process, many facets will be taken into consideration. However, the performance of a turbine is dominated by the flow in it. The simulations of flow details in a Pelton turbine were conducted in the present work and a kind of negative flow that is two jets flow into the same bucket was detected and evaluated. It will affect the efficiency and the torque character of Pelton turbine. After that, several factors were investigated to find ways to improve the flow condition in the turbine which is proved to be effective. The work will contribute to the design of Pelton turbine.

1. Introduction

In mountainous area, high head power plants are quite popular, therefore, Pelton turbine is widely used according to its structural characteristics [1]. A Pelton includes 4 major parts i.e. collector, injector, bucket and housing [2]. All the energy including potential and kinetic parts is converted into velocity through a contracting nozzle and then drive the bucket [3, 4]. Because of its simple and rigid structure, it runs steadily and easy to be maintained. Furthermore, variation of discharge influences lightly to working condition. The design of the buckets geometry considers to increase the operating time of the runner and avoiding the cavitation [5]. As a working principle, water jet runs into the symmetrically shaped buckets, then the jet is split into two parts which forms a thin sheet of water on the bucket's surface [6]. Indeed, the flow is unsteady, 3D and has a free surface for the water jet and in the bucket [7]. Furthermore, the flow in the bucket is a moving thin sheet of water which produces negative flow irregularly. Importantly, this process is just the energy transmitting process which effects the efficiency of Pelton turbine.

The key issue for a better design of runner is to simulate accurately the flow phenomena [5, 8]. In the recent decades, Computational Fluid Dynamics (CFD) becomes a useful tool for the design and manufacture of Pelton turbines [9, 10]. However, accurate simulation of the flow phenomena in Pelton turbines is still a challenging task. Kubota et al [11] stepped firstly into the computer supported hydraulic design of Pelton runners. Parkinson et al [12] made some assumptions of free jet flow and then used Finite Difference Method (FDM) to simulate the flow in Pelton turbine. They conclude that there exists a low speed region near the center of the jet and the size of the region depends on the opening of the injector nozzle. Zoppe et al [13] preformed numerical study which was conducted in the laboratory of LEGI for two-phase flows. The Piecewise Linear Interface Calculation (PLIC) method [14] was used for the geometrical reconstruction of the interface. The results agree well with



their corresponding experimental results. As secondary flow produced along the collector influences the jet shape and jet quality, Staubli et al [15] and Vesely et al [16] investigated a Pelton turbine numerically and experimentally and proved that this is also a direction to improve the efficiency. Three adjacent buckets was simulated by Mack [8]. Kvicinsky et al. [17] firstly attempted to simulate free surface flow in a rotating bucket. Marongiu et al. [18] focused the same case as Kvicinsky et al. [17] to validate their particle-based solver. Jost et al. [19] confirmed the importance role of grid refinement to simulate accurately the flow of a Pelton distributor and two injectors using the two-phase homogeneous model. Xiao et al. [20] preformed Lagrangian computation which estimates the integral pressure. However, this method cannot provide the exact water sheet location or precise pressure field. Perrig [21] deeply researched the initial jet-bucket interaction or the jet cut process, and take into account the secondary forces, *i.e.* surface tension and viscosity to improve the design of the backside. Furthermore, a detailed analysis indicates that the shape of the water jet influences on the energy losses and the stator influences the efficiency [22]. Sick et al. [23] concluded that jet-bucket interaction has impact on excitation and detuning of the runner.

In this paper, simulations of flow in a Pelton turbine were conducted and a kind of negative flow in it was detected. Several facts were investigated to find how to improve the flow condition in the turbine. The work will contribute to the design of Pelton turbine.

2. Case description and numerical scheme

The scaled turbine studied in the paper has 17 buckets and 2 nozzles. The runner diameter of the turbine is $D=1300\text{mm}$. Jet diameter of nozzle is $d=140\text{mm}$. The diameter ratio $M=D/d=9.2$. The angle between two nozzles is 75° . Figure 1 shows the model. The model is divided into 3 parts for the simulations - distributor, runner and the related space.

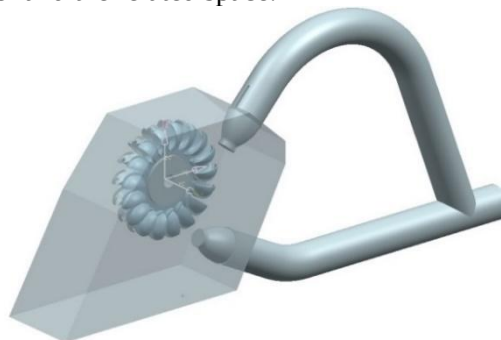
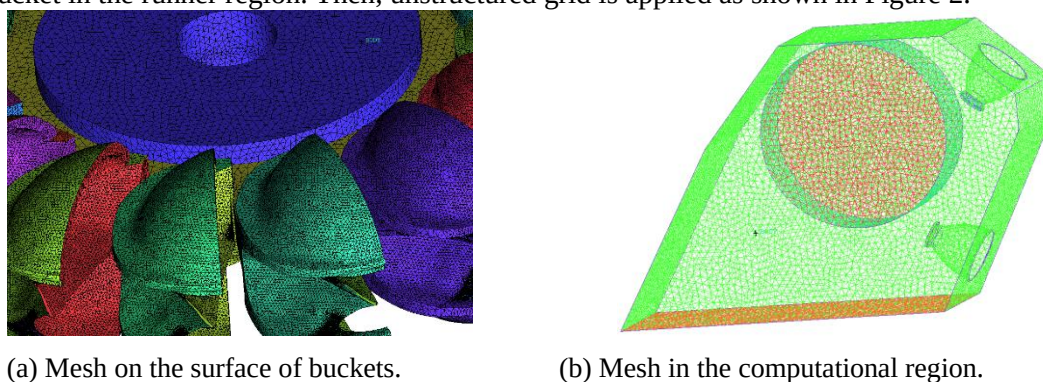


Figure 1. Model of turbine studied in the paper.

The mesh for the calculations is generated by commercial software ANSYS ICEM. The computational region of the turbine can't be discretized by structured grid because of the sharp tip on the bucket in the runner region. Then, unstructured grid is applied as shown in Figure 2.



(a) Mesh on the surface of buckets.

(b) Mesh in the computational region.

Figure 2. Mesh generated.

The turbine efficiency at the operation point $n_{11}=40\text{r/min}$, $Q_{11}=34\text{l/s}$ is chosen to validate the mesh. Figure 3 shows the efficiency of the turbine under different grid number. When the grid number is more than 15 million, the efficiency of the turbine changes little with grid number. A suit of grid with 15 million is chosen for the simulations in the paper.

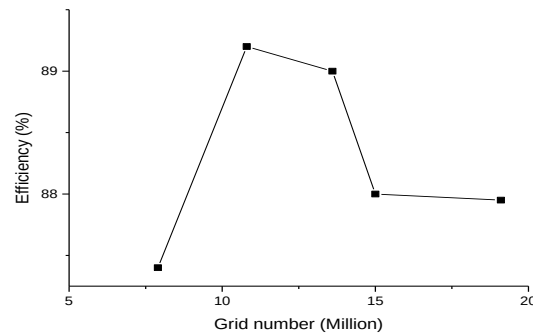


Figure 3. Mesh sensitivity check.

VOF model was used to compute the two-phase flow in the turbine. According to the real conditions, the distributor is filled with water, and the initial condition of volume fraction of water in distributor is set as 1. The initial condition of volume fraction of water in runner region is set as 0 (filled with air). Flow rate in the inlet of distributor is given. The outlet pressure 1atm is set as outlet of the whole system. In the recent, Best Efficiency Point (BEP) $n_{11}=40$ is often selected, and the velocity ratio is 0.48. Runner speed of 500 rpm is set for the calculations.

3. Results and discussions

It is important to detect the flow in a single bucket because the working process of Pelton turbine is completed through the interaction between the water and the bucket. The results of VOF model can show clear interface of different phases and can show the distributions of different phases. It is possible to obtain the instantaneous flow conditions in the turbine at different time

Figure 4 and Figure 5 shows the working process of the Pelton turbine. Figure 4 shows the process that the water flushes into the bucket. Figure 5 shows the process that the water flows out of the bucket.

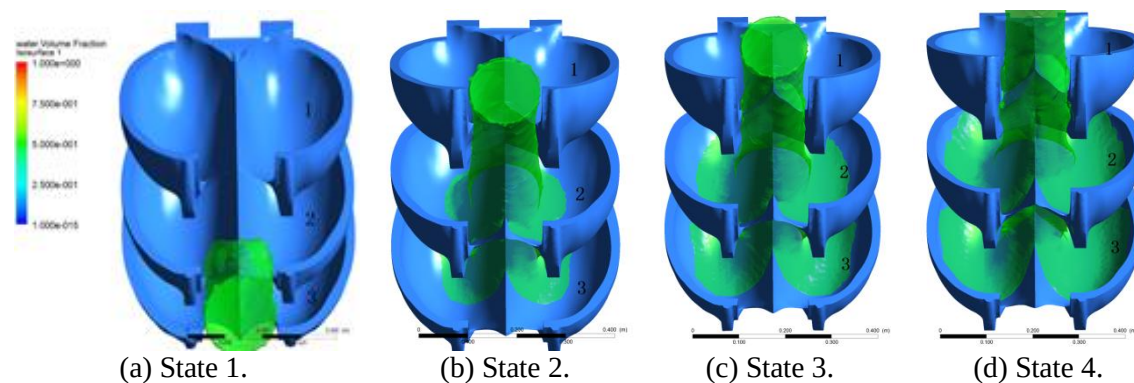


Figure 4. The process that the water flashes into the bucket.

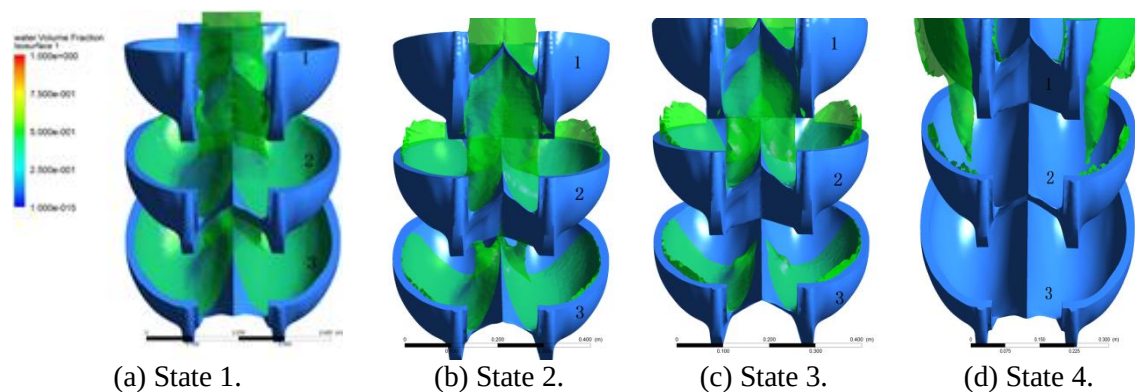


Figure 5. The process that the water flows out of the bucket.

Figure 6 shows the torque on bucket in a cycle. Time $t=0.05s$ in Figure 6 refers to the state in Figure 4(a). The jet flow is running into the bucket, the interaction between jet flow and bucket will produce little positive torque on the bucket because the jet will also flow onto the back of the bucket. Then, the jet-flow flushes into the bucket crossing the water knockout blade. And minus torque will produce on the bucket. With the increase of the water flowing into the bucket, the magnitude of minus torque will increase. When the jet-flow is blocked by the former bucket, the magnitude of minus torque on bucket will begin to decrease. The bucket will repeat the above procedure when the bucket running into the next jet.

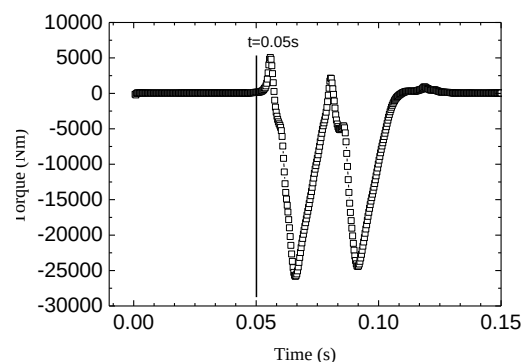


Figure 6. Toque profile on bucket.

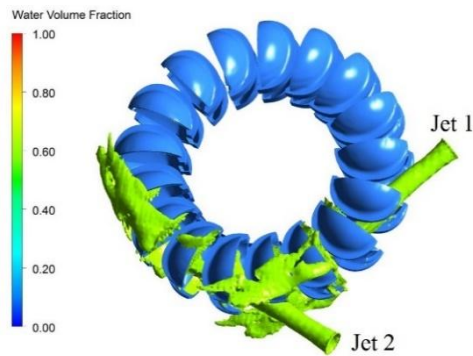
3.1. Analysis on the phenomenon that two jets flow into the same bucket

It is a common phenomenon that two jets flow into the same bucket in middle and small size Pelton turbine.

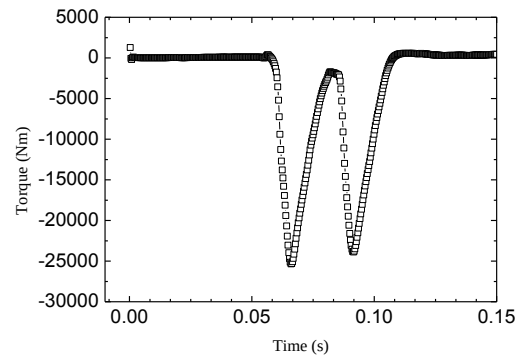
In multiple-nozzle Pelton turbine, the efficiency of the turbine will be heavily decreased if the jet-flow rushes into the bucket if the water from former jet has not flowed out of the bucket thoroughly.

Figure 7(a) shows the flow condition in the Pelton turbine, $\alpha=75^\circ$; $\psi=0.48$. The phenomenon mentioned exists in bucket. Water from Jet 2 flows into bucket when the water from Jet 1 has not flowed out of bucket thoroughly which heavily deflect the work condition of the turbine.

Figure 7(b) shows the torque-time profile on bucket. At time $t=0.055s$, the torque on bucket is not rising rightly though the water from jet 2 has already rushes into the bucket, which leads to the decreasing of torque when the bucket goes through jet 2. And this will lead to the decrease of working capacity when the bucket goes through jet 2. The efficiency of the turbine under these parameters is 76.28% (Average). The average torque on the bucket during the period of going through jet 1 is 9170N m, while the average torque on the bucket during the period of going through jet 2 is 7960N m.



(a) Flow condition in Pelton turbine.



(b) Torque-time profile on the bucket.

Figure 7. Flow character of original turbine.

The phenomenon is related to two times. The one is the time that the bucket running from the former jet to the later jet (T_1), the other is the period between the water rushes into the bucket and flows out of the bucket (T_2). Generally, the phenomenon will happen if $T_1 - T_2 \leq 0$ and vice versa.

$$T_1 = t_2 - t_1 = \frac{\theta}{\omega} \quad (5)$$

θ -Angle between two nozzles.

ω -speed of runner

V -Jet velocity

t_1 -time when the bucket is at position 1

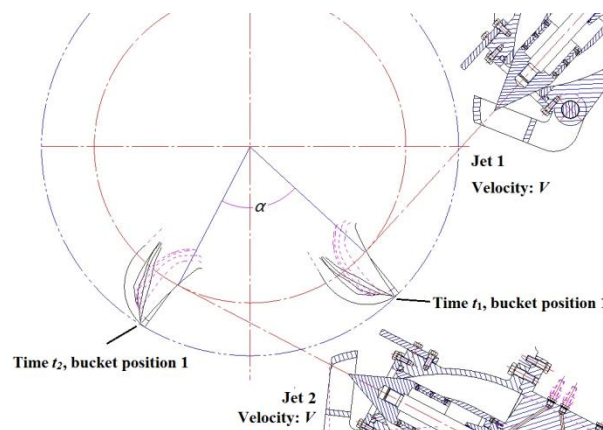
t_2 -time when the bucket is at position 1

$$T_2 = \frac{C}{V} \quad (6)$$

C - Constant.

Figure 8 describes the principle of the phenomenon.

It is to say, the phenomenon is related only on the three parameters of the turbine α , ω and V .

**Figure 8.** Sketch of two jets flow into the same bucket.

During the design processing, rotational speed of generator is a constant, i.e. runner angular speed keeps unchanged. Then, we can decrease or eliminate the influence of the phenomenon by changing the angle between two nozzles (α) or jet velocity (V).

Four strategies are selected in the paper to investigate the facts that will influence the phenomenon. S1: set only one nozzle for the turbine and compare the character of the turbine with that of the two-nozzle one. S2: change the angle between two nozzles (α) and compare the character of the turbine with that of original turbine. S3: change the jet velocity (V) and compare the character of the turbine with that of original turbine. S4: change the diameter ratio (M) and compare the character of the turbine with that of original turbine.

3.2. Flow character in single nozzle turbine

There will not be this kind of phenomenon because there is only one nozzle in the turbine and the flow field in the turbine is shown in Figure 9. The comparison between the result and the result of original model can tell us the influence grade of the phenomenon. And the results can be taken as the standard to judge if the phenomenon exists.

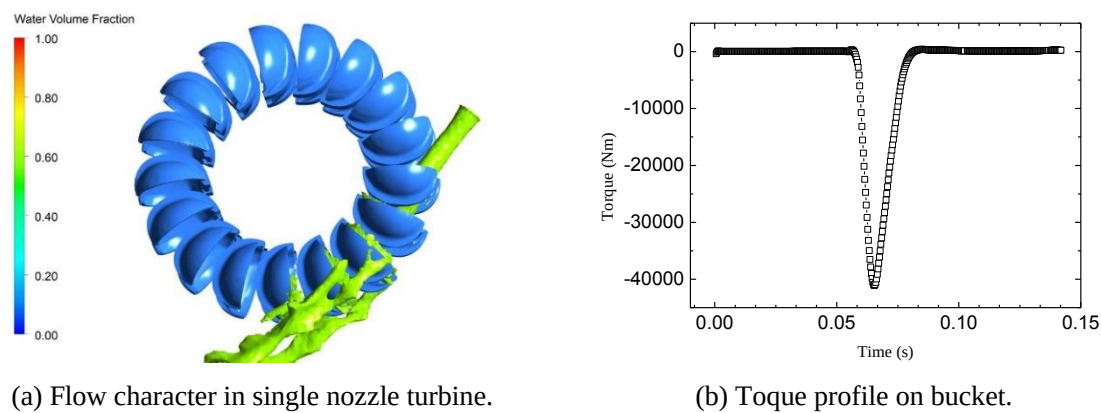


Figure 9. Flow character in single nozzle turbine.

Table 1 shows the comparison between the efficiency of single-nozzle turbine and the efficiency of original model. The efficiency of single-nozzle turbine is 7.95% higher than that of two-nozzle turbine, which implies that the phenomenon that two jets flow into the same bucket has a negative effect on the efficiency and working capacity of Pelton turbine.

The efficiency of single-nozzle turbine is higher because the phenomenon that two jets flow into the same bucket does not exist in single-nozzle turbine. However, single-nozzle turbine can't be used in power stations because the working capacity can't satisfy the need of plants.

Table 1. Comparison between single-nozzle turbine and two-nozzle turbine.

Model	Diameter ratio M	Angle ($^{\circ}$)	Velocity ratio ψ	Efficiency (%)
two-nozzle turbine	9.2	75	0.48	76.28
single-nozzle turbine	9.2	/	0.48	84.23

3.3. Change the angle between two nozzles α

The phenomenon that two jets flow into the same bucket will be prevented if $T_1 - T_2 \geq 0$ is satisfied. And from Eq. (2) we know that T_1 will increase if α increases.

180°, 110° and 90° are set for the angle between two nozzles (α) to study the influence on the performance of the turbine.

180° is a limit of α , and $T_1 - T_2 \geq 0$ can be absolutely satisfied. Figure 10 (a) shows that the water has thoroughly flowed out of the bucket when the second jet goes into the bucket, which indicates that, the phenomenon that two jets flow into the same bucket has been avoided. And this also can be drawn out in Figure 10 (b). The peak and average value of torque on the bucket during the second jet is

almost the same as that during the first jet. The efficiency of the turbine with angle between two nozzles $\alpha=180^\circ$ is 84.26%. It is lot higher than the efficiency of the turbine with angle between two nozzles $\alpha=75^\circ$. The disadvantage of the turbine with angle between two nozzles $\alpha=180^\circ$ is that the distributor will undertake more space in the power station.

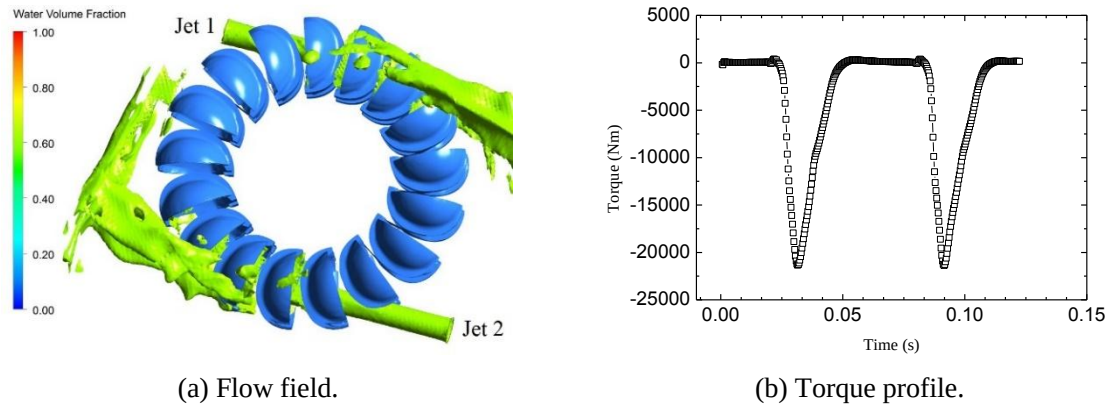


Figure 10. Flow conditions when the nozzle angle is 180° .

Figure 11 (a) shows that the water has thoroughly flowed out of the bucket when the second jet goes into the bucket, which indicates that, the phenomenon that two jets flow into the same bucket has also been avoided. And this also can be drawn out in Figure 11 (b). The pink and average value of torque on the bucket during the second jet is almost the same as that during the first jet. From Table 2 we know that the efficiency of the turbine with angle between two nozzles $\alpha=110^\circ$ is 84.16%. The efficiency and the working capacity are improved a lot with comparison to the turbine with angle between two nozzles $\alpha=75^\circ$.

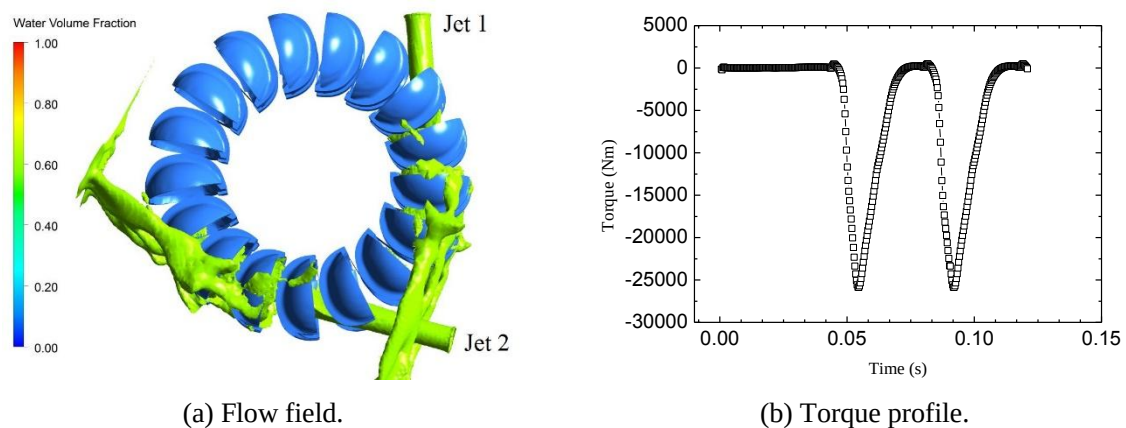


Figure 11. Flow conditions when the nozzle angle is 110° .

Figure 12 (a) shows that the water has almost flowed out of the bucket when the second jet goes into the bucket, which indicates that, the phenomenon that two jets flow into the same bucket has not been completely avoided for the turbine with angle between two nozzles $\alpha=90^\circ$. However the pink and average value of torque on the bucket during the second jet is almost the same as that during the first jet (see Figure 12 (b)). From Table 2 we know that the efficiency of the turbine with angle between two nozzles $\alpha=90^\circ$ is 84.14%. The efficiency and the working capacity do not decrease heavily. From above analysis, it can be indicated that the phenomenon does not influence the performance of the turbine a lot. In this case, it can be considered as a critical state for the turbine to avoid the phenomenon that two jets flow into the same bucket.

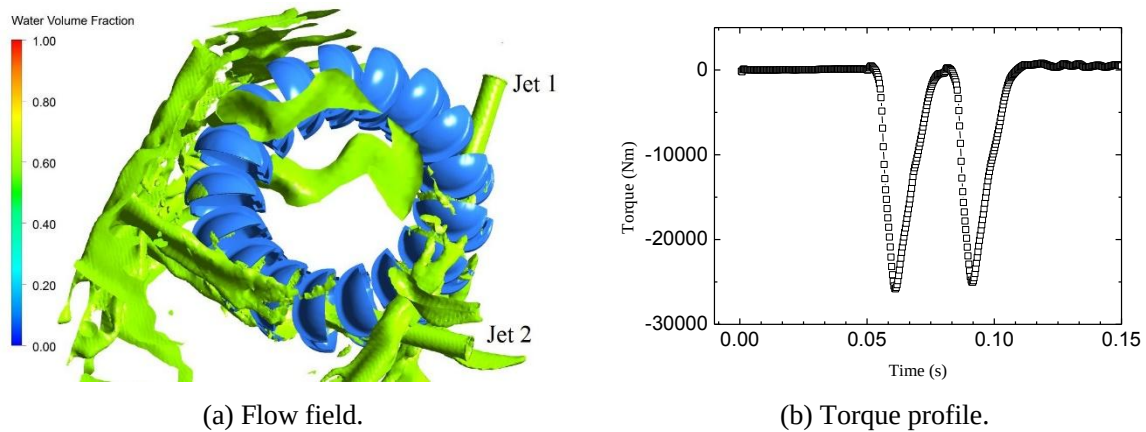


Figure 12. Flow conditions when the nozzle angle is 90 °.

Table 2. Comparison of different conditions.

Nozzle angle (°)	Diameter ratio M	Velocity ratio ψ	Efficiency(%)
75	9.2	0.48	76.28
180	9.2	0.48	84.26
110	9.2	0.48	84.16
90	9.2	0.48	84.14

3.4. Change the jet velocity V

Velocity ratio (ψ) is usually use in the study of Pelton turbine. It is defined as:

$$\psi = V_t / V \quad (4)$$

Where,

V_t –Tangential velocity of runner at pitch-circle, $V_t = \omega \times r$, ω angular speed and radius of runner at pitch-circle respectively;

V – Velocity of jet.

ω and r keep constant, then ψ and V are in inverse proportion.

T_2 will decrease if V increases. And we can change the value of T_1 - T_2 through adjusting the value of V . The phenomenon will be prevented if V is large enough. We select conditions of $\psi=0.045$, $\psi=0.42$ and $\psi=0.35$ to investigate the flow character of the Pelton turbine as shown in Table 3.

Table 3. Conditions selected for velocity ratio.

Conditions	Case II	Case III
Velocity of runner at pitch circle V_t (m/s)	34.02	34.02
Jet velocity V (m/s)	81.5	97.8
Velocity ratio ψ	0.42	0.35

We define $L=M_1/M_2$. M_1 and M_2 is the average torque during the bucket goes through the first nozzle and the average torque during the bucket goes through the second nozzle respectively. $L=1$ states that the negative phenomenon does not exist in the turbine and $L>1$ states the opposite. For the original turbine, $L=1.152$.

Figure 13 to Figure 14 show the flow conditions and torque profile under different conditions. And Table 2 lists the value of L under different conditions.

When $\psi=0.42$, $L=1.04$, which indicates the negative flow is improved though exists in these two conditions. When $\psi=0.35$, $L=1.0008$, the negative flow almost disappeared in this condition. The negative phenomenon that two jets flow into the same bucket can be prevented by changing velocity ratio, i.e. jet velocity, however the changing of velocity ratio will decrease the efficiency of the turbine at BEP point.

Table 4. Results of changing velocity ratio.

Conditions	Case II	Case III
Velocity ratio ψ	0.42	0.35
Torque ratio L	1.04	1.0008

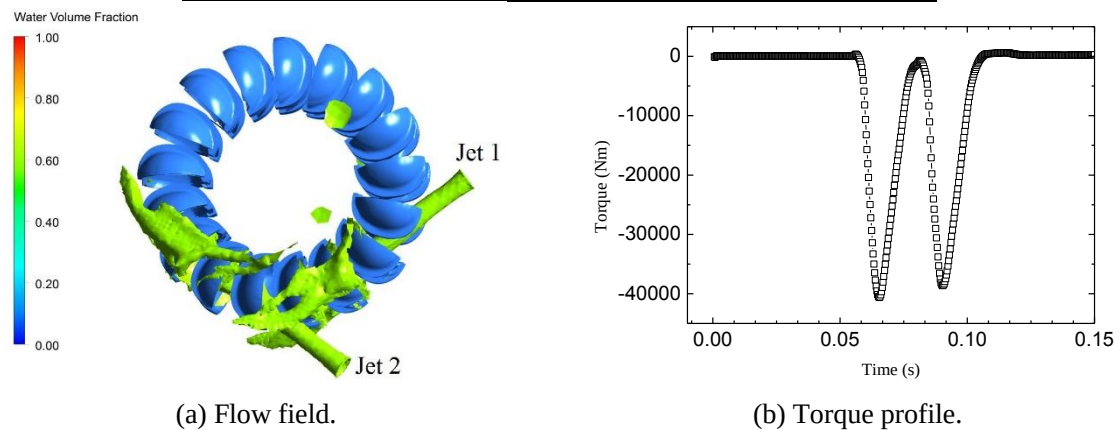


Figure 13 Flow conditions under velocity ratio $\psi=0.42$.

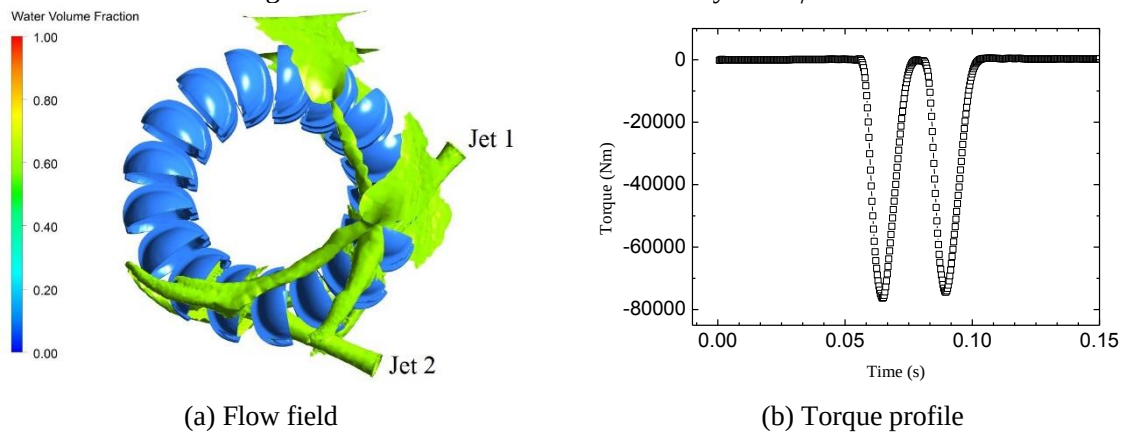


Figure 14 Flow conditions under velocity ratio $\psi=0.35$.

4. Conclusions

The paper studied the negative flow in a Pelton turbine that two jets flow into the same bucket and calculated how the phenomenon influence the performance of Pelton turbine.

The negative flow can be prevented by changing the angle between two nozzles (α) and the velocity ratio (ψ).

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