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OBSERVATION OF JET INTERFERENCE IN 6-NOZZLE PELTON TURBINE

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1. INTRODUCTION

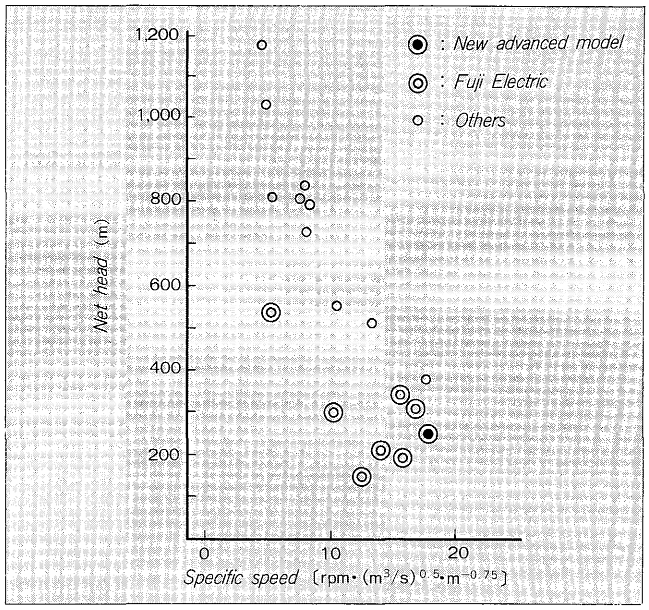
A Pelton turbine has been applied to higher heads. In recent years, it is applied to medium to low heads less than 100m. This trend is due to the re-evaluation of the following advantages of Pelton turbines:

1. Through the regulation of the number of nozzles, a multi-nozzle Pelton turbine can be operated under the wide range of output power maintaining high efficiency without vibration increase, compared with a Francis turbine. In other words, the vari-discharge characteristics of a multi-nozzle Pelton turbine are excellent.
2. Since a deflector in front of each nozzle can deflect a jet in a moment from the runner through its rapid closure, the penstock pressure rise after the load rejection or during the sudden stop can be kept to a minimum by slowly closing the needles.
3. The operation of a Pelton turbine using the deflectors to maintain the discharge gives the possibility of eliminating the surge tank and/or overflow channel which results in the reduction of civil cost.
4. During the turbine stop, a runner, nozzles and so forth can be accessible without draining water, thus easy for inspection and maintenance.

The greatest reason of expediting the application of a Pelton turbine to the lower head is in the success of increasing the specific speed of a Pelton turbine. The higher specific speed is achieved by increasing the number of nozzles and the rotational speed. As a result, turbines and generators become compact, and the construction cost of power houses is reduced. For these reasons, the demand for 6-nozzle high specific speed Pelton turbines is growing. *Table 1* shows the recent records to Fuji Electric for the 6-nozzle Pelton turbines. *Fig. 1* reveals the trend of net head versus specific speed.

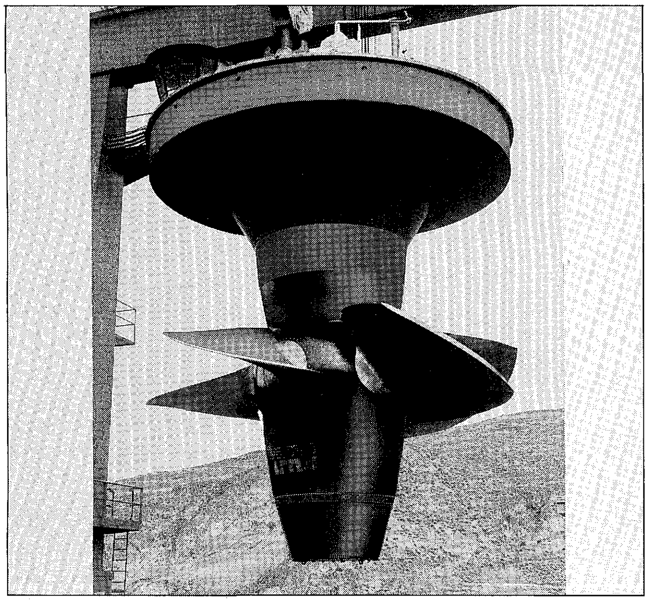
When the number of nozzles and the rotational speed is increased and the specific speed reaches a certain limit, the jet from the second nozzle may enter into a bucket before the water from the first nozzle discharges out from the bucket. The entering second jet interferes violently with the discharging water in the runner bucket. This is the phenomenon well known as jet interference. If the specific speed of a multi-nozzle Pelton turbine is selected too high, jet interference will result from the reason explained in the following sections. Jet interference prevents the regular flow in the buckets and results in the sharp deterioration of turbine output power with cavitation and vibration. In other words, jet interference is the biggest obstacle preventing the increase in specific speed of multi-nozzle Pelton turbines. To avoid this jet interference, there has been no choice but to limit the specific speed to a certain value, so far.

Fig. 1 Net head versus specific speed of 6-nozzle Pelton turbines



In spite of jet interference being the most important phenomenon to be clarified for increasing the specific speed of multi-nozzle Pelton turbines, hardly no research has been conducted on this subject in the past. The flow in the Pelton runner is the three dimensional time-dependent intermittent flow with the free-surface of variable water thickness which is inherent to the impulse turbine, different from the runner of a reaction turbine. The precise and reliable numerical flow analysis methods have not been established, and the flow inside the bucket

Fig. 11 Inserted runner (site, integrated with old top cover)



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6. CONCLUSION

Installation and testing of the first unit was completed and commercial operation began in March 1988. Factory work was completed with the shipment of the tenth runner in March 1990. Completion of installation and testing of the tenth unit is forecast for July 1990.

As previously mentioned, rehabilitation of existing aging hydroelectric power plants is excepted to increase in the future. The authors will be happy if this material serves in the planning of these projects.

Table 1 Fuji Electric records of 6-nozzle pelton turbines (since 1982 in operation)

Power Plant	Country	Unit	Output (MW)	Net head (m)	Specific Speed ($rpm \cdot (m^3/s)^{0.5} \cdot m^{-0.75}$)	Operation (year)
Pyramid	USA	2	43.3	218.2	17.0	1982
Sultan River	USA	2	57.0	340.0	14.2	1984
Terror Lake	USA	2	13.67	385.0	16.6	1984
Calderas	Columbia	2	14.0	176.5	15.0	1988
Bradley Lake	USA	2	63.12	335.3	17.8	Construction
Ohzaso	Japan	1	12.0	215.55	17.0	Construction

of a Pelton runner can not be investigated numerically. Also, the three dimensional splash of water films and droplets discharging from the runner buckets prevent the visual observation of model turbines in the hydraulic laboratory. The only indication of jet interference, so far, was the sharp efficiency deterioration during the efficiency tests.

To ascertain jet interference in multi-nozzle Pelton turbines, a model test was performed in Fuji Hydraulic Laboratory to visually observe the flow in the rotating buckets in which the water from two adjacent nozzles may interfere. Through the specially provided windows, jet interference in the rotating bucket which has only been assumed so far, was clearly observed and photographed. In addition, it was confirmed that a part of the sharp efficiency deterioration can be attributed to the jet disturbance outside of runner buckets. In this paper, the relationship between the specific speed and jet interference, and the result of visual observation of jet interference and jet disturbance are reported.

2. SPECIFIC SPEED AND JET INTERFERENCE

When the rotational speed N of a Pelton turbine is specified under the heat H and rated discharge Q, the specific speed N_{sq} is calculated with the following equation:

$$N_{sq} = NQ^{0.5}/H^{0.75} \quad (1)$$

The discharge Q is expressed with the jet diameter d_j, the velocity of jet v_j and the number of nozzle Z as follows:

$$Q = (\pi d_j^2/4)v_j Z \quad (2)$$

Using the jet velocity constant C_v, the velocity is

$$v_j = C_v(2gH)^{0.5} \quad (3)$$

The peripheral speed constant C_{u1} at the runner representative (jet pitch circle) diameter D_1 is

$$C_{u1} = \pi D_1 N/[60(2gH)^{0.5}]. \quad (4)$$

Substituting equations (2) ~ (4) into equation (1), the specific speed is

$$N_{sq} = [30(2g)^{0.75} C_{u1} C_v^{0.5}/\pi^{0.5}] Z^{0.5} d_j/D_1. \quad (5)$$

When the size of runner bucket is represented by the inner width of bucket, the bucket width B is given, as the function of jet diameter d_j, by the following equation which gives the constant value of approx. 3.0:

$$C_b = B/d_j. \quad (6)$$

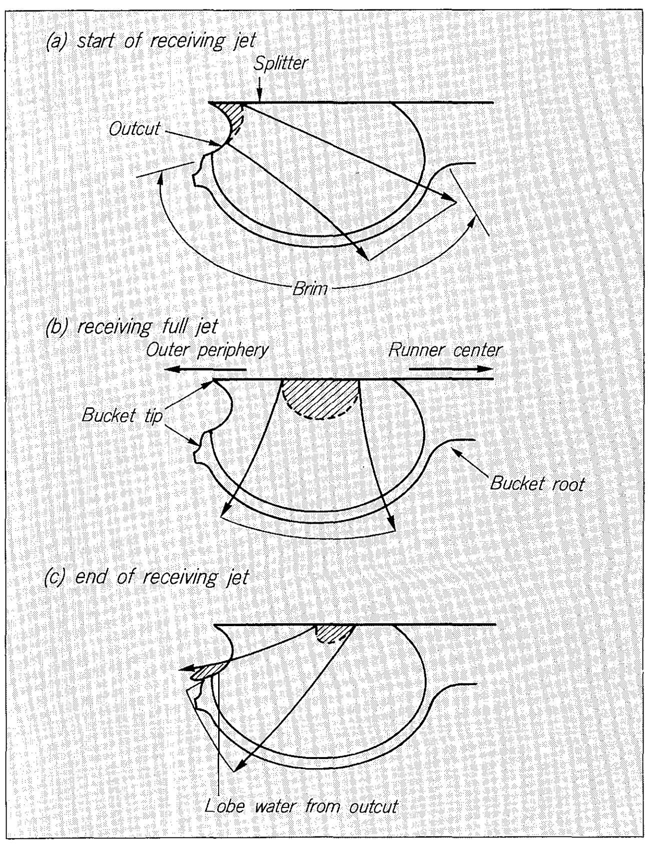
Substituting equation (6) into equation (5) and replacing all constants with C_{nq}, the specific speed is

$$N_{sq} = C_{nq}Z^{0.5}B/D_1. \quad (7)$$

In order to increase the specific speed of a Pelton turbine, it is necessary to increase the number of nozzles and the bucket width per unit runner diameter.

When the number of nozzles is increased, the rotational angle of a bucket from a moment when the bucket starts to receive a jet, to a moment when the same bucket starts to receive the adjacent jet, becomes small. In the case of a 6-nozzle turbine, the rotational angle between the two adjacent jets is 60 degrees. Meanwhile, the increase in bucket width per unit runner diameter necessitates the reduction of the number of buckets due to the spatial

Fig. 2 Flow along bucket



restriction, thus the rotational angle in which the water stays on the bucket becomes larger. The flow in the bucket will be explained in detail in Chapter 4 and here, a basic idea is presented as follows.

When a rotating bucket touches a jet emerging from a nozzle, at first, the outcut of the bucket receives the jet. The water flows inwardly, against the centrifugal force, from the outcut to the root through the bucket as shown in *Fig. 2 a)*. As the bucket rotates, it penetrates into the jet and receives more of the jet with the splitter, and the water on the splitter flows toward the brim of the bucket as shown in *Fig. 2 b)*. At the final stage of receiving jet, the water on the splitter flows toward the outcut as in *Fig. 2 c)*. It means that the outcut of the bucket is the trailing edge where the water from the first nozzle discharges out, and also, is the leading edge where the second jet enters. This is the reason for the possibility of jet interferences when the specific speed is increased.

As a result, the ratio of the bucket width to the runner diameter B/D_1 of multi-nozzle turbines has been limited to the certain value. Here, the analysis on the jet interference is described using a high specific speed 6-nozzle model Peltron turbine with large B/D_1 focusing mainly on the visual observation of flow in the bucket.

3. TEST STAND AND MODEL TURBINE

Figs. 3 and *4* show the section and plan of a high specific speed 6-nozzle model Pelton turbine with N_{sq} of 19 rpm·m³/s·m. *Table 2* shows the test conditions and the size of model turbine. Jet interference and jet disturbance were observed through the special windows attached to a model turbine. A total of 12 acrylic flat windows were provided on each wall of a hexagonal housing to lighten the jets and the runner buckets. It was, however, not possible to observe the inside of buckets through the flat windows, because the water which was discharged from the upper half of the runner buckets, flowed along the inner wall of housing and curtained the windows.

Fig. 3 Section of model turbine

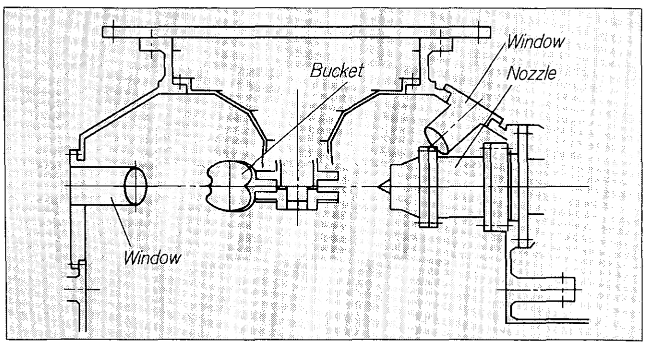


Fig. 4 Plan of model turbine

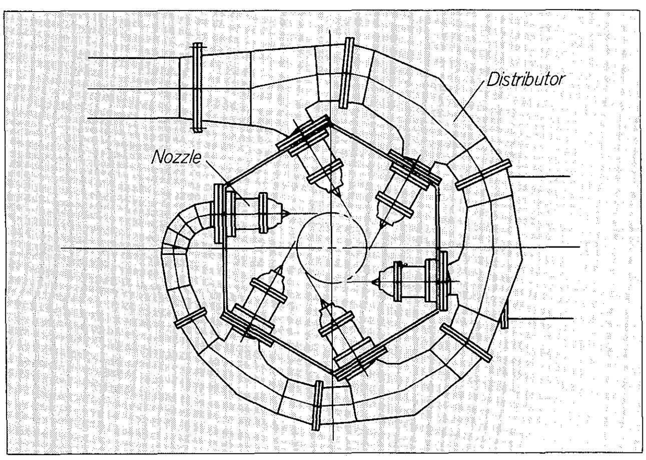


Table 2 Test conditions and size of model turbine

net head	(H)	approx. 60 m
discharge	(Q)	approx. 0.3 m³/s
rotational speed	(N)	approx. 800 rpm
specific speed	(N_{sq})	19 rpm·m³/s·m
jet pitch circle dia.	(D_1)	0.3746 m

The acrylic cylindrical pipes were inserted as shown in *Fig. 3* to minimize as much as possible the water splash between an observer and the relevant bucket. Their opening was placed as close to the bucket as possible. These pipes are made transparant to avoid disturbing the lighting through the flat windows. Also, the deflector is removed from the nozzle to be examined for easy observation of jets and the flow inside the buckets.

4. MODEL TEST AND OBSERVATION RESULT

4.1 Observation of flow in 1-nozzle operation

In this section, the observation of the flow in 1-nozzle operation is explained which is the basis for the observation of jet interference. *Figs. 5(a)* and *7(a)* show the relative position of a bucket to a jet at a certain (explained later) moment. *Figs. 5(b), 6(b)* and *7(b)* are photographs viewing laterally a model runner during the 1-nozzle operation at the same moment as the respective *Figs.(a)*, where a jet from a nozzle on far right runs toward the left, flows into buckets and rotates the runner from right to left. And *Figs. 5(c), 6(c)* and *7(c)* are those looking askance at the same model at the same moment as *Figs. (b)*, where a jet from a nozzle at the right front runs to the deep left, flows into bucket appeared at the center of the photo and turns the runner clockwise when viewed from the top. The notation 5-① or 6-②, for example, in *Figs. 5 – 7* indicates Bucket 1 in *Fig. 5*, Bucket 2 in *Fig. 6*, etc.

Fig. 5 shows a schematic drawing and photographs at the moment when the outcut of Bucket 1 contacts a jet. Beyond this moment, the only residural jet after cut off by Bucket 1 will flow into Bucket 2. Therefore, it is the last chance for Bucket 2 to receive an entire jet. *Fig. 6* shows a drawing and photos at the moment when the runner has turned approx. 7° in rotational angle from the position shown in *Fig. 5*. The outcut of Bucket 1 is now into approx. the middle of a jet, receiving about a half

Fig. 5 Flow at a moment when a bucket touches a jet.

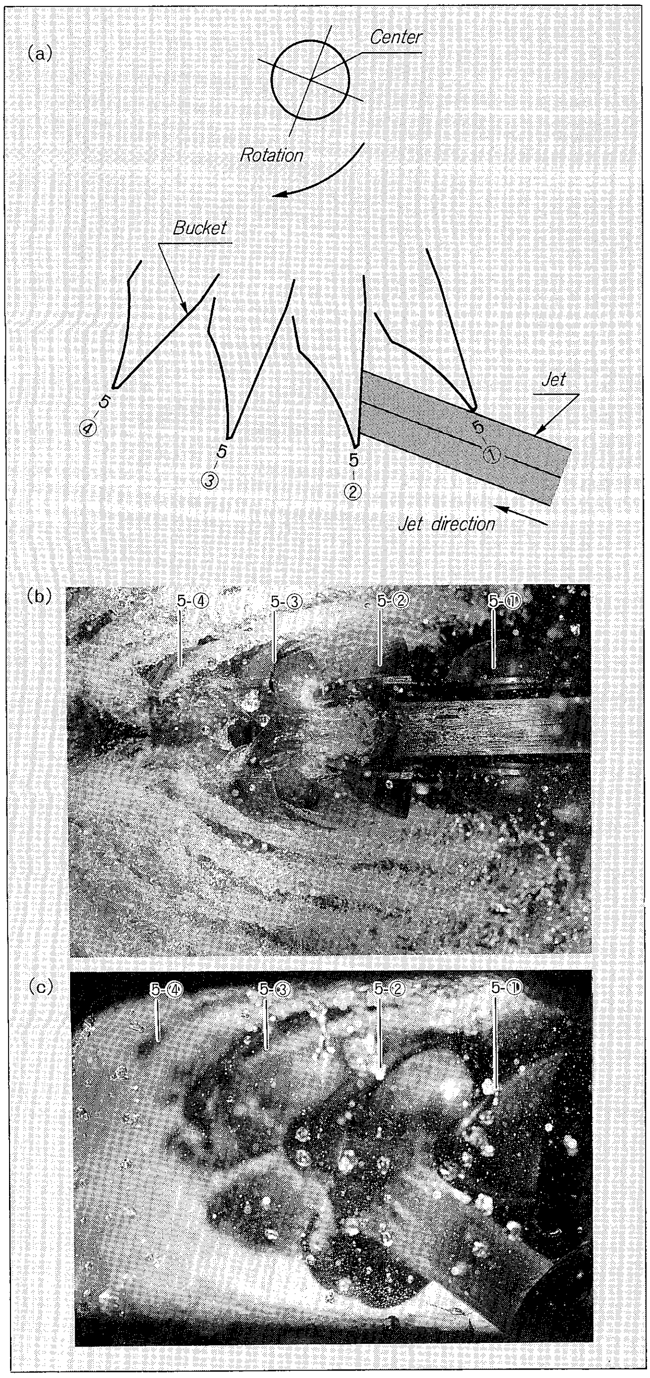
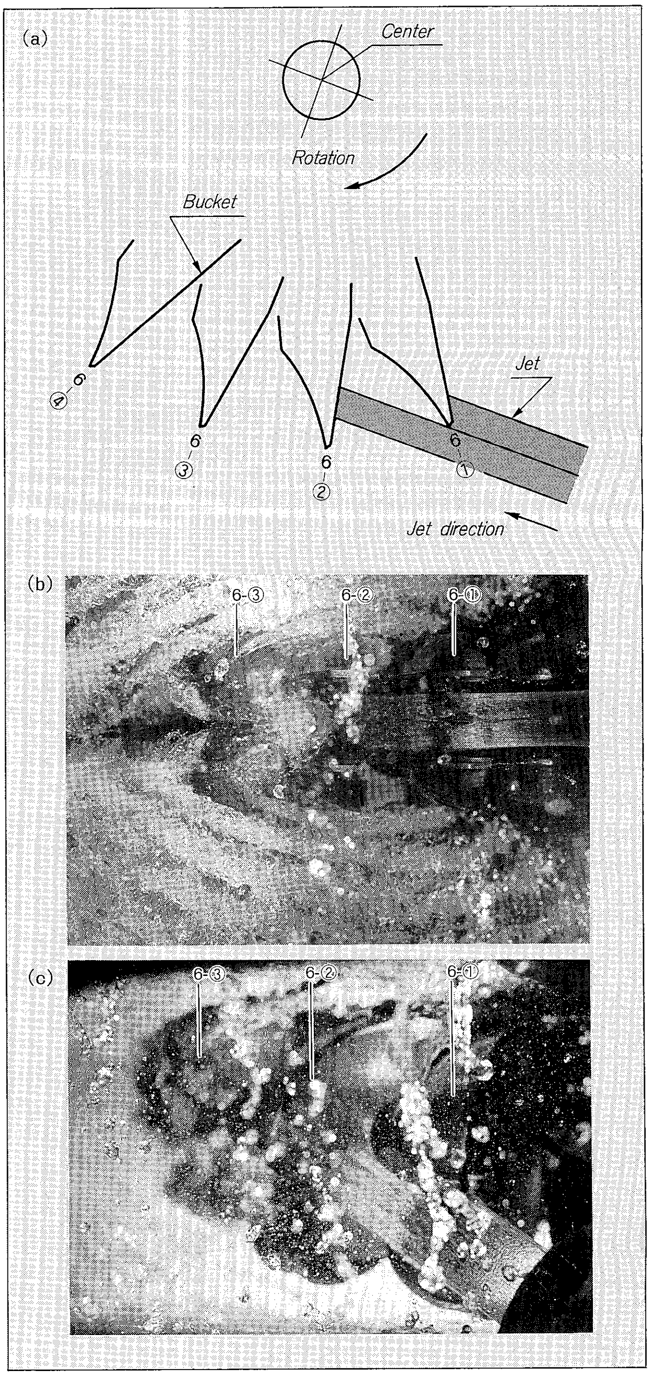


Fig. 6 Flow at a moment when a bucket receives half a jet.



the jet at the inner side (centre side). The Bucket 2 receives the residual half at the outer side (nozzle side). Shown in *Fig. 7* are the drawing and photos of the runner turned further to the left at approx. 8° in rotational angle and the Bucket 1 has received about an entire jet. The Bucket 2 at this moment is still receiving the jet before cut off by the Bucket 1, however, since the velocity of the jet is higher than the peripheral speed of the bucket, the Bucket 2 will receive only the residual jet beyond this point.

The water which entered through the outcut of the Bucket 1 at the position of 5-①, flows across the bucket radially inward as shown in *Fig. 2(a)*, then flows out from the innermost periphery of the bucket trailing edge (near the bucket root) at the position 6-② (Bucket 2 in *Fig. 6*). The position of water discharge from a bucket moves along the trailing edge, from the inner periphery (near the root) to the outer periphery (7-②, 5-③, 6-③) and eventually reaches the outcut on outer-most periphery (7-③). Also the water entered through a splitter at the center of bucket at the position 6-② flows across the bucket outward, then beings to flow off from the outcut in the position 5-③, as shown in *Fig. 2(c)*. This water whose shape is a pair of lobes overflowing the outcut,

Fig. 7 Flow at a moment when a bucket receives a full jet.

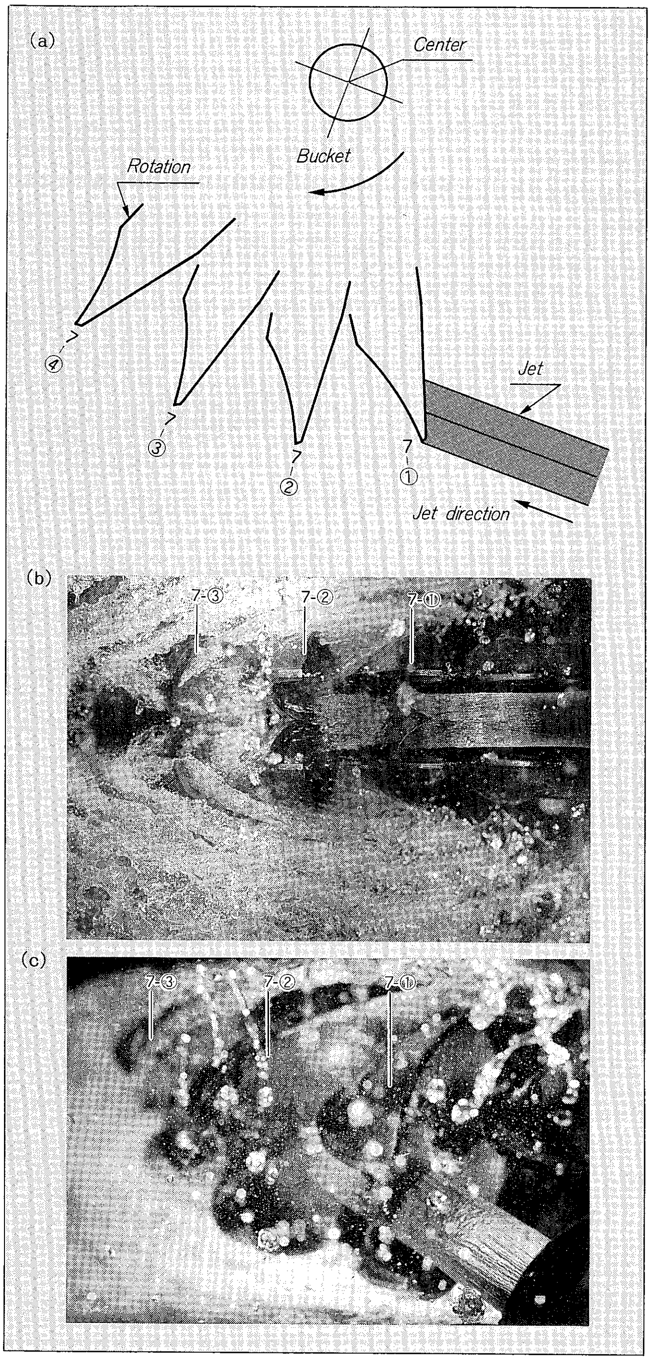


Fig. 8 Flow discharging from the outlet of rotating buckets.

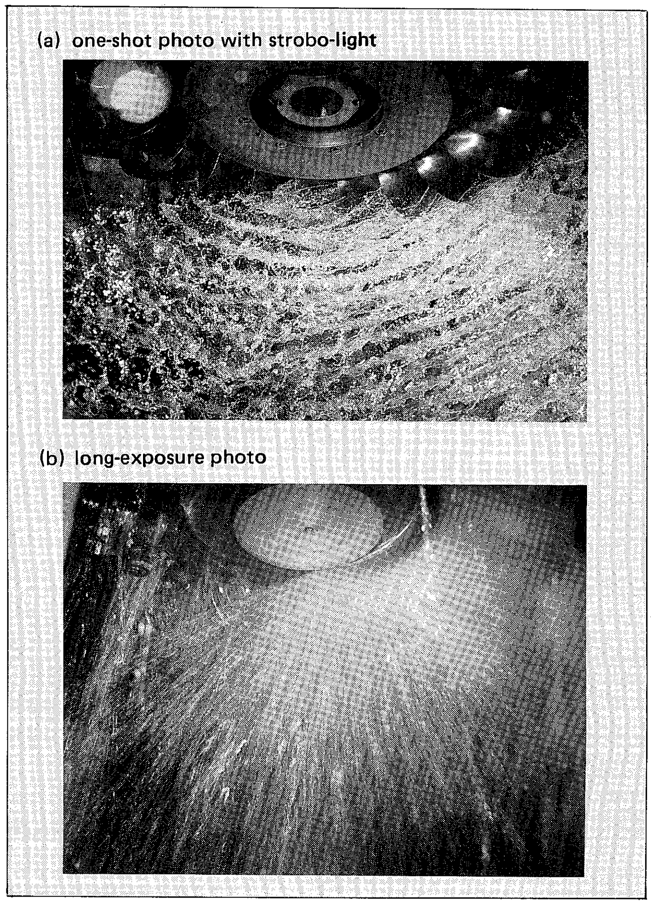
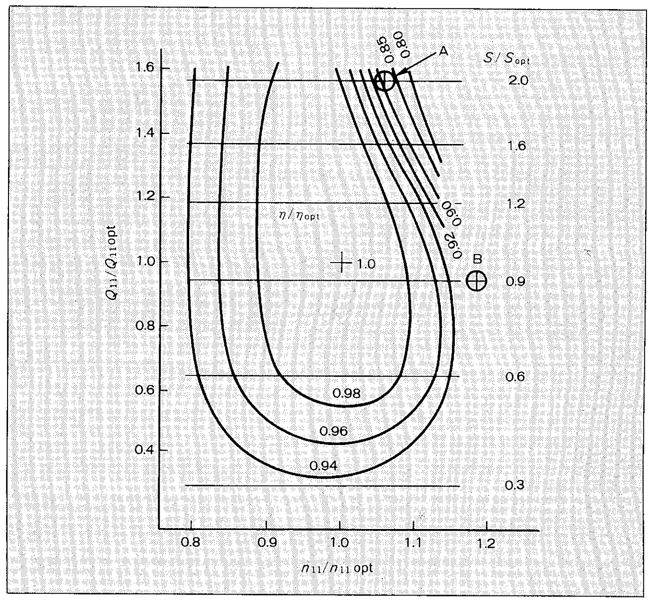


Fig. 9 Efficiency deterioration due to jet interference.



grows 6-③ and further at 7-③. If a new jet from the next nozzle enters into the outcut at this condition, the occurrence of jet interference is easily assumed.

Fig. 8 shows the other side of runner looking from underneath. *Fig. 8(a)* is an instantaneous photo from the light of stroboscope and *Fig. 8(b)* is a long-exposure photo. In both photos, a jet from the nozzle in far deep left runs toward the right, flows into the buckets and rotates the runner in counterclockwise looking from underneath, however neither the nozzle nor the jet can be seen from this position. From the figure, it is clearly understood that the emerging water appears first at the root of bucket, and the emerging position shifts along the brim of buckets toward the outcut. The water splash is in wide range, and is reached to the deflector of adjacent nozzle (far right) suggesting the possibility of jet disturbance mentioned later.

Fig. 10 Flow in a bucket without jet interference (1-nozzle operation).

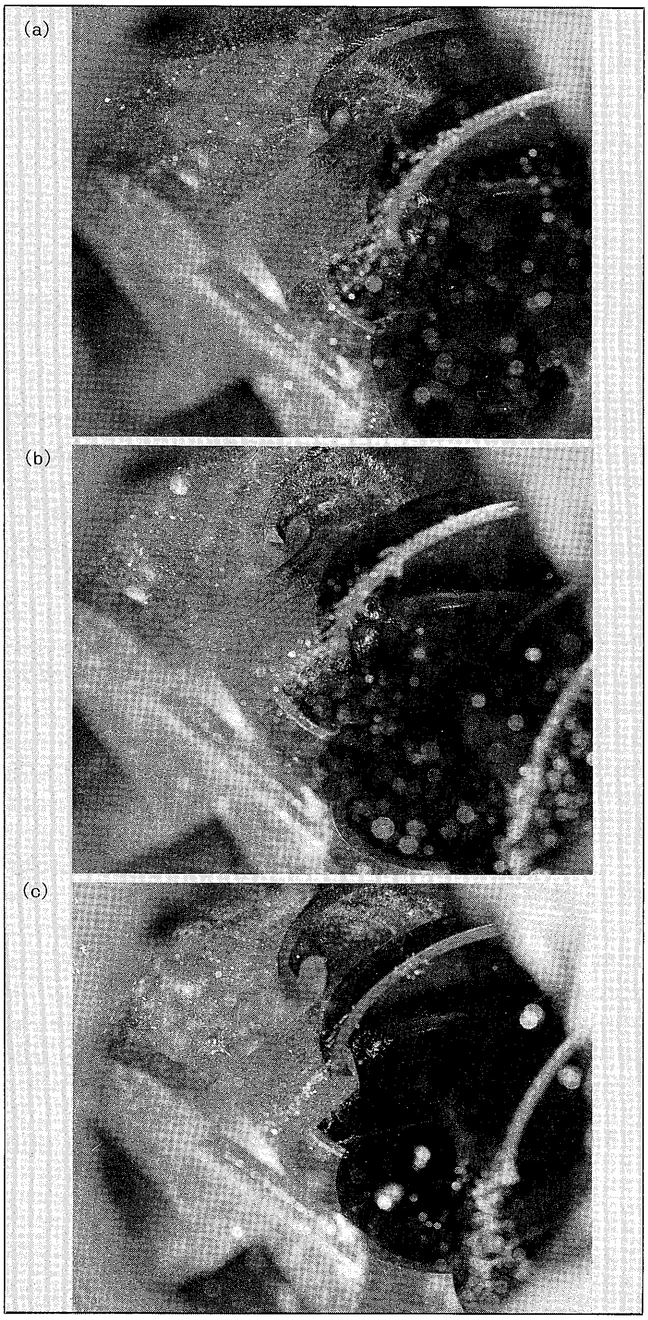
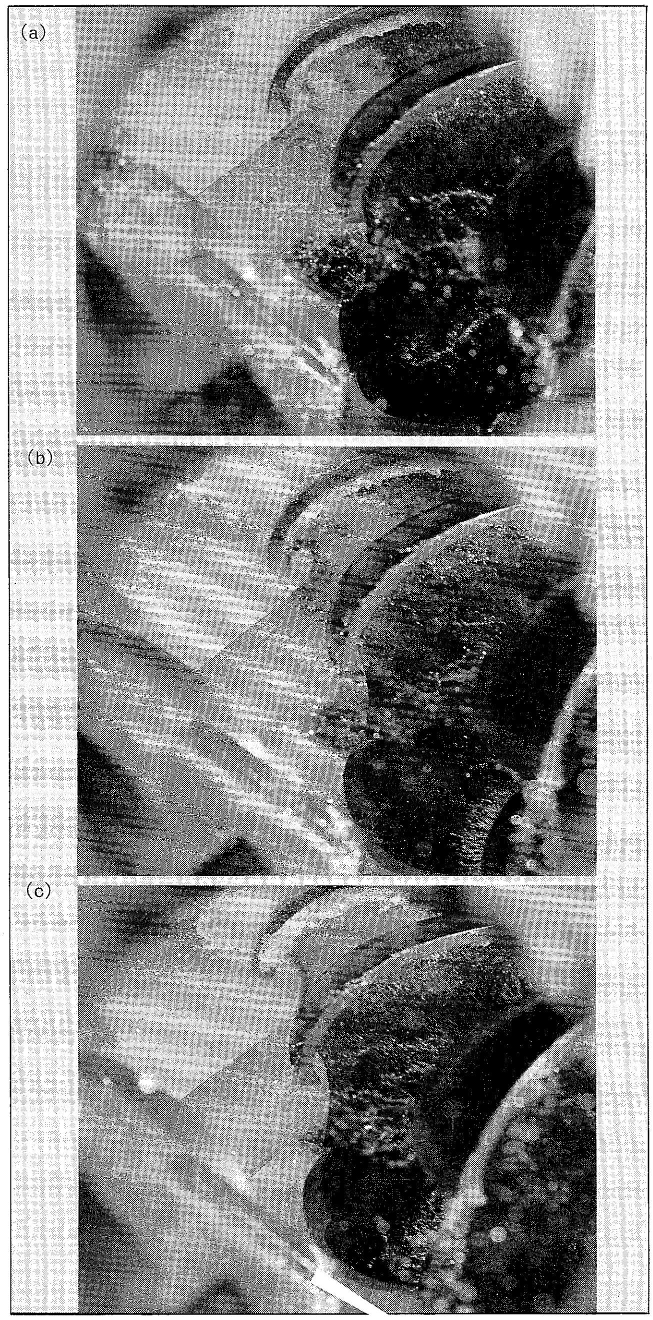


Fig. 11 Flow in a bucket with jet interference (2-nozzle operation).



4.2 Observation of flow in 2-nozzle operation

4.2.1 Jet interference in bucket

Fig. 9 shows the efficiency characteristics of the model turbine in 6-nozzle operation. The specific speed N_{sq} is expressed in terms of unit speed N_{11} and unit discharge Q_{11} as follows:

$$N_{sq} = N_{11} Q_{11}^{0.5} \qquad \cdots\cdots\cdots\cdots (8)$$

In *Fig. 9*, the operating specific speed becomes large in the region where the values of both N_{11} and Q_{11} are large. In other words, on the upper right of *Fig. 9*, the jet interference tends to occur, and actually, is confirmed with the sharp efficiency deterioration.

The flow was observed mainly at the operating point with the needle stroke $S/S_{opt} = 2.0$ and the unit speed $N_{11}/N_{11opt} = 1.06$ (Point-A in *Fig. 9*) where sharp efficiency deterioration occurs due to the jet interference. The water splash inside the housing is particularly severe in 6-nozzle operation which disturbs the observation of the jet and flow inside the buckets. Meanwhile, jet interference occurs between the two adjacent jets. Thus the observation was concentrated in the adjacent 2-nozzle operation and a jet from the second nozzle.

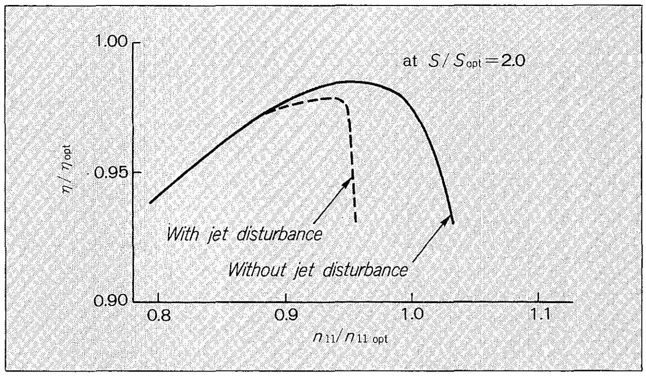
As a result, jet interference was clearly observed as follows. A jet from the first nozzle that enters into the splitter of a bucket is flowing toward the outcut as 5-③ in *Fig. 5*, and clearly interferes with the jet from the second nozzle. However, the photograph taken at this operating point was extremely unclear because of the strong water splash. Consequently S/S_{opt} was lowered from 2.0 to 0.9 in order to reduce the water splash. Photograph was concentrated on the operating point $N_{11}/N_{11opt} = 1.18$ (Point-B in *Fig. 9*) where the turbine efficiency shaply deteriorates with this needle-stroke as a result of the jet interference. *Figs. 10* and *11* show photos of the flow on bucket's inner surface. Both *Fig. 10(b)* and *Fig. 11(b)* are the photographs showing the moment when the runner has turned approx. 4° in rotational angle to the left from the position in *Fig. 10(a)* and *Fig. 11(a)*. *Fig. 10(c)* and *Fig. 11(c)* are the moment when the runner has turned approx. 4° further to the left. Shown on the lower left is the second nozzle and the runner buckets are on the upper right. The jet emerges out from the front left toward the back right and turns the runner clockwise when looking from the top. Photos were taken by the one-shot stroboscope light.

The only difference between *Fig. 10* and *Fig. 11* is the number of nozzles in operation. *Fig. 10* shows 1-nozzle operation with only the second jet. *Fig. 11*, on the other hand, shows the adjacent 2-nozzle operation with jets from the second nozzle in the photo and the first nozzle (on the right) not shown in the photo. A close observation of both photos points out an important difference in two areas – one is the landing spot of the jet from the second nozzle flowing into the bucket and the other is the flow through the first nozzle discharged from the bucket's outer brim. That is, in *Fig. 10*, the landing spot of jet on the bucket surface is transparent, due to the 1-nozzle operation and no jet interference. In *Fig. 11*, by contrast, it is opaque near the landing spot of jet from the second nozzle on bucket surface, since this is the adjacent 2-nozzle operation and a severe water crash is occurring on the bucket surface. The severity of jet interference increases from *Fig. 11(a)* to *Fig. 11(c)*. These are clear photos of jet interference on the bucket's inner surface.

4.2.2 Jet disturbance out of bucket

The amount and intensity of flow discharged from the outer brim of a bucket adjacent to the outcut (7-③, 5-④, and 7-④ in *Figs. 5 – 7*) become larger and stronger as the needle-stroke becomes larger at the operating point ($S/S_{opt} = 2.0$, $N_{11}/N_{11opt} = 1.06$) where the jet interference was observed. Since the discharging positions on both sides of jet offset each other in the axial direction, usually the discharging water does not directly disturb the jets. However, for high specific speed 6-nozzle Pelton turbines, the volumetric space of nozzle and deflector that occupies the housing is large, thus the free space inside the housing is so small that the water discharged from the outermost periphery of bucket is deflected by the nearest surfaces of deflector and nozzle toward the jet which emerges from the second nozzle. As a result, it was confirmed that the water from the outermost periphery of bucket is deflected by a deflector inner-radially toward the second jet, then disturbs the jet before flowing into the bucket and causes the efficiency deterioration as shown in *Fig. 12*. In the figure, the curve "without jet disturbance" shows the performance at $S/S_{opt} = 2.0$ of turbine efficiency curves in *Fig. 9* of a turbine with the push-out deflectors.

Fig. 12 Efficiency deterioration due to jet disturbance.



Since a push-out deflector will protect the jet just out of a nozzle, no jet disturbance will occur. On the other hand, "with jet disturbances" shows the turbine efficiency for the case where the push-out deflectors are replaced by the cut-in deflectors. A cut-in deflector can not protect the jet out of a nozzle, and the water splashed back by the deflector disturbs the jet, therefore, the efficiency deterioration is considerable.

As the results of the optimization of the bucket shape to minimize the amount of water discharging from the outcut of buckets, as well as of the deflector shape to minimize the amount of water splashing back based on the above visual observation, both the jet interference in the buckets and jet disturbance outside of buckets can be reduced, and the critical specific speed of 6-nozzle Pelton turbine has been increased by more than 25%.

5. CONCLUSION

The visual observation of flow in a model runner for a high specific speed 6-nozzle Pelton turbine has revealed that the sharp deterioration of efficiency in large Q_{11} and high N_{11} region is caused by jet interference in the buckets and jet disturbance outside of the bucket.

1. The jet from the first nozzle which enters into a bucket from the splitter and is going to discharge out at the outcut of the bucket, is interfered with by the jet from the second nozzle which has just entered into the outcut of the same bucket. The jet interference was clearly observed and photographed through the special windows.
2. If the jet from the first nozzle which has discharged out at the outer brim of a bucket, is splashed radially outward and deflected by the nearest surfaces of deflector and/or nozzle to the outer surface of the second jet, severe jet disturbance occurs with the sharp efficiency deterioration.