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Index Method for Pumping Operation of Reversible Pump-Turbine^{1,2}

The adaptability of the Winter-Kennedy index method [1]³ was examined, and consequently "Draft Tube Index Method" for Francis and diagonal flow pump-turbines under pumping operation were newly investigated experimentally. It is clarified that the Winter-Kennedy method is applicable to Francis pump-turbines, but not suitable to apply on diagonal flow pump-turbines with adjustable guide vanes, and that the draft tube index method, depending upon differential pressure between two pressure taps provided on the draft tube or on the air-pipe, indicates sufficient accuracy to apply on Francis and diagonal flow pump-turbines.

Introduction

In order to operate a pumped storage power station economically, it is necessary to determine hydraulic input of the pump-turbine and electric output of the generator-motor for turbine operation, and to ascertain electric input of the generator-motor and hydraulic output of the pump-turbine for pumping operation, respectively. Electric input/output and head, among the aforementioned values, are comparatively easy to measure with high precision; however, the measurement of rate of flow is often accompanied by various errors, requiring considerable time and labor. In a hydraulic power station, therefore, an index method is sometimes employed instead of the measurement of rate of flow under which an indicated value—or relative discharge—is substituted for the absolute rate of flow.

Regarding the index method for turbine operation, the results of application of this method have already been reported by Vouden [2]. Several methods are classifiable under the index method of which most widely used are the Winter-Kennedy method [1] and the Peck method [2]. The former is based on differential pressure between two pressure taps on the spiral casing; the latter method is based on differential pressure between two pressure taps on one of the stay vanes. However, to our knowledge no appropriate application data of an index method for pumping operation have been reported to date.

This paper describes the applicability of the Winter-Kennedy method and draft tube index method for both Francis and diagonal flow pump-turbines under pumping operations. The facts obtained are as follows:

1 The location of the pressure taps for the Winter-Kennedy method must be carefully selected for Francis pump-turbines. This method is very difficult to apply to diagonal flow pump-turbines (cf., Fig. 2).

2 A draft tube index method, depending upon differential pressure between two pressure taps provided on the draft tube or on the air pipe, has satisfactory applicability as an index method under pumping operations.

Consequently, the draft tube index method is proposed in this paper.

Experimental Equipment and Method

Model pump-turbines used in this experiment were two Francis pump-turbines and one diagonal flow pump-turbine as specified in Table 1. Of the two types of Francis pump-turbines prepared for experiment, model (A) was a Francis pump-turbine with fixed guide vanes, and model (B) was a Francis pump-turbine with adjustable guide vanes. Diagonal flow pump-turbine, model (C), is the type of adjustable guide vanes and blades. For the Francis pump-turbine (B), pressure taps were provided at the (s) position on the suction tank and at positions (1)–(14) on the draft tube (cf., Figs. 3 and 4). For the diagonal flow pump-turbine (C), pressure taps were arranged at the (s) position on the suction tank, positions (1)–(15) on the draft tube, positions (16)–(19) on the air pipe, and positions (20)–(25) on the spiral casing (cf., Figs. 5 and 6).

Differential pressure for index was measured with mercury and water manometers, water and air manometers, or water and oil manometers, depending on the measuring conditions. Discharge and head, respectively, were measured by using a weighing tank and a mercury manometer. In addition, an automatic measuring balance was used for measuring shaft torque, and the number of revolutions were measured by a magnetic pulse transmitter and an electric pulse counter.

Relationship between the pressure difference in the pressure taps and the discharge was examined in full detail by changing the opening of the guide vanes and blade angle of each model pump-turbine.

Results of Experiment

General Performance of Model Pump-Turbines. The results of experiment are shown after converting them to a condition where pump-turbine speed $N = 1000$ rpm. Fig. 1 shows the general performance curves of the diagonal flow pump-turbine. The discharge (Q_m) at maximum efficiency and the discharge (Q_r ($h_{r,11}$)) at the beginning point of reverse flow of the differential pressure ($h_{r,11}$)—referred to in a subsequent section—are shown in it.

The Winter-Kennedy Method. Illustrated in Fig. 2 are examples of data obtained from the application of the Winter-Kennedy method for the fixed guidevane type Francis pump-turbine (A) and the diagonal flow pump-turbine (C) under pumping operation. In the Francis pump-turbine, the following relation can be observed between discharge (Q) and differential pressure ($h_{i,j}$) in the range of $\log Q > 1.9$. That is,

$$Q = k \cdot h_{i,j}^n \quad (1)$$

¹ Communicated by Prof. Emeritus Dr. F. Numachi. Mem. ASME.
² Presented by L. P. Brown, Project Engineer, Allis-Chalmers, Hydraulic Products Division, York, Pa. Mem. ASME.

³ Numbers in brackets designate References at end of paper.
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PERFORMANCE CURVES DIAGONAL FLOW PUMP TURBINE - PUMPING

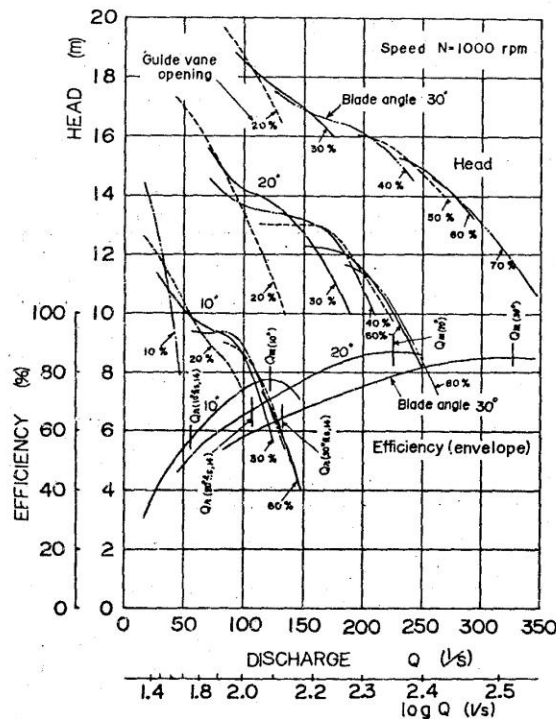


Fig. 1 General performance curve of diagonal flow pump-turbine (C)

where, $k = \text{const}$; $h_{i,j}$ = differential pressure (cm Aq) was obtainable after deducting the pressure in pressure tap (j) from that in pressure tap (i).

However, the measuring points had a tendency to form a snaking motion. The other Francis pump-turbine with adjustable guidevanes (specific speed $N_s = 40 \text{ m}^{-3}/\text{s}$; experimental result omitted here) indicated the same tendency. In the diagonal flow pump-turbine, variations of the measuring point for the graphically shown differential pressure $h_{21,24}$ had a more remarkable tendency to display a snaking motion of each guidevane opening differential pressure against discharge than did the Francis pump-turbine. In addition—although omitted here—the exponent value n varied, depending on the blade angle in case of the diagonal flow pump-turbine. Therefore, this characteristic was unfavorable for index method. This trend remained the same even in the differential pressures of $h_{21,23}$ and $h_{23,22}$.

FIXED GUIDE VANE FRANCIS TYPE PUMP TURBINE (A) & DIAGONAL FLOW PUMP TURBINE - PUMPING

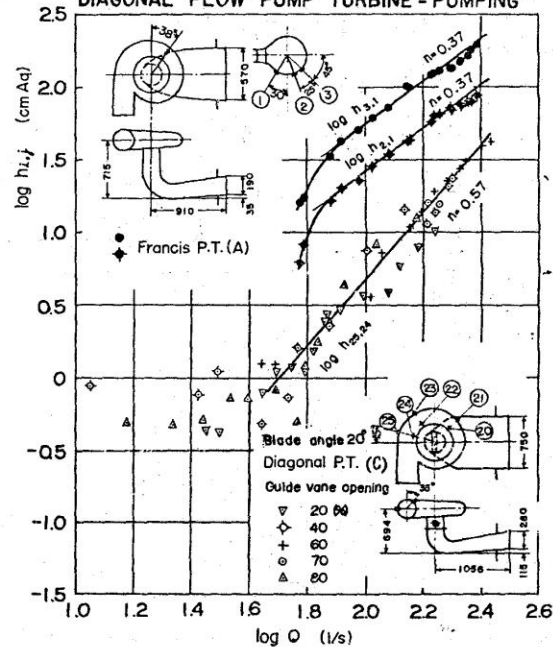


Fig. 2 Winter-Kennedy method applied to pumping operation

Since the spiral casing under pumping operation is on the downstream side of the runner and guidevanes, the flow in the spiral casing is influenced by the runner and the guide vanes. In this case, therefore, the value of n in equation (1) and the degree of variation of the measuring point would be affected on the guide vane opening and blade angle. When applying the Winter-Kennedy method to pump-turbine under pumping operation, it is necessary to carefully examine the discharge range to which this method is applicable and to consider the precision required.

Draft Tube Index Method. The draft tube index method proposed in this report is explained as follows. When discharge exceeds a certain fixed value in the event of pumping operations, the flow is in the regular direction approximately, but as the discharge grows smaller, reverse flow occurs in the runner. If this discharge becomes increasingly smaller, the reverse flow is gradually extended to the upstream of the draft tube. Therefore, the draft tube index method, based on the static pressure value on the draft tube wall surface, is closely related to the reverse flow characteristics of a pump-turbine.

Table 1 Dimensions of model pump-turbines

	Francis pump-turbine (A)	Francis pump-turbine (B)	Diagonal flow pump-turbine (C)
Outside diameter of runner (mm)	430	280	325
Inside diameter of runner (mm)	256	150	200
Number of runner-blades	7	7	8
Blade angle of runner	Fixed	Fixed	Adjustable
Height of guide vane (mm)	45	20	75
Number of guide vanes	16	20	20
Guide vane opening	Fixed	Adjustable	Adjustable
Specific Pump (m^{-3}/s)	40	30	60
speed Turbine (m-kw)	145	100	210

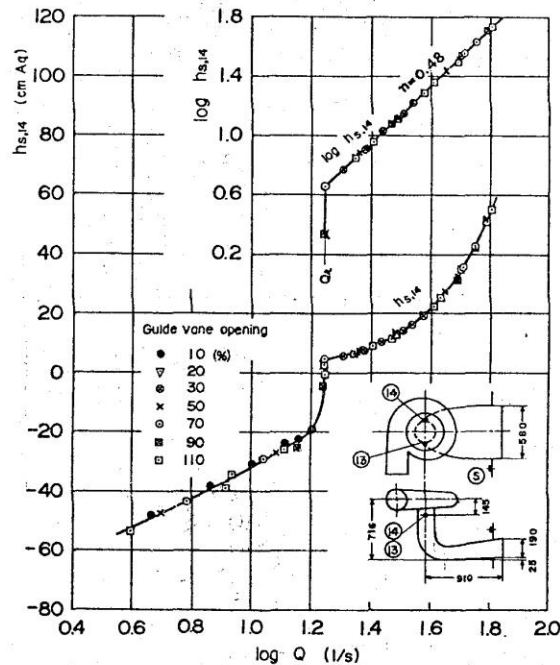


Fig. 3 Characteristics of draft tube index method applied to Francis pump-turbine (B)

Draft Tube Index Method Applied to Francis Pump-Turbine. Shown in Figs. 3 and 4 are examples of the results of application of the draft tube index method to the Francis pump-turbine (B). As shown in these two figures, two remarkable tendencies are observable. The differential pressure $h_{s,14}$ is abruptly decreased to a negative (-) value in the range of $Q < Q_r$ as shown in Fig. 3. On the other hand, as shown in Fig. 4, the differential pressure $h_{s,j}$ shows a minimum value at the point of $Q = Q_r$ or $Q = Q'_r$. This Q_r position is one where its pressure tap begins to be influenced by reverse flow, the discharge at this position is hereafter referred to as the "beginning discharge of reverse flow" (indicated by Q_r).

Fig. 3 shows data on the condition when one of the two pressure taps is located at the (14) position on the draft tube, close to the runner; the other tap is located at the (s) position on the suction tank wall. In the range of $Q > Q_r$, there is no noticeable influence of the guidevane opening on the differential pressure ($h_{s,14}$), in addition satisfying equation (1). In the range of $Q < Q_r$, the differential pressure $h_{s,14}$ turns into a negative value (-) abruptly, and—even in this range—no noticeable difference due to guidevane opening is observable. This tendency remained experimentally the same even in the pressure tap (13).

Fig. 4, the other side, reveals data of the condition where one of the pressure taps is located at the bending portion (12) of the draft tube and at positions (2), (6) on the upper stream side of that bending portion, while the other pressure tap is located at the (s) position. Any combination of pressure taps satisfies equation (1) in the range of $Q > Q_r$. If discharge becomes smaller than Q_r or Q'_r , $h_{s,j}$ again becomes larger. When these pressure taps are applied to the index method, two discharges are consequently obtained against one-differential pressure ($h_{i,j}$) in a certain discharge range; thus these taps are not suitable to the index method practically. On the contrary, the pressure taps, as shown in Fig. 3, are pressure taps to which the index method can be satisfactorily applied, because only one discharge is obtained against one-differential pressure ($h_{i,j}$).

Draft Tube Index Method Applied to Diagonal Flow Pump-Turbine. Fig. 5 reveals the index characteristics of the differential

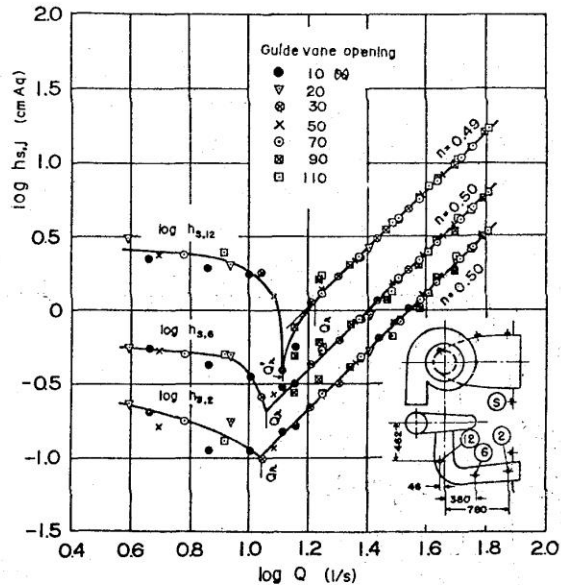


Fig. 4 Characteristics of draft tube index method applied to Francis pump-turbine (B)

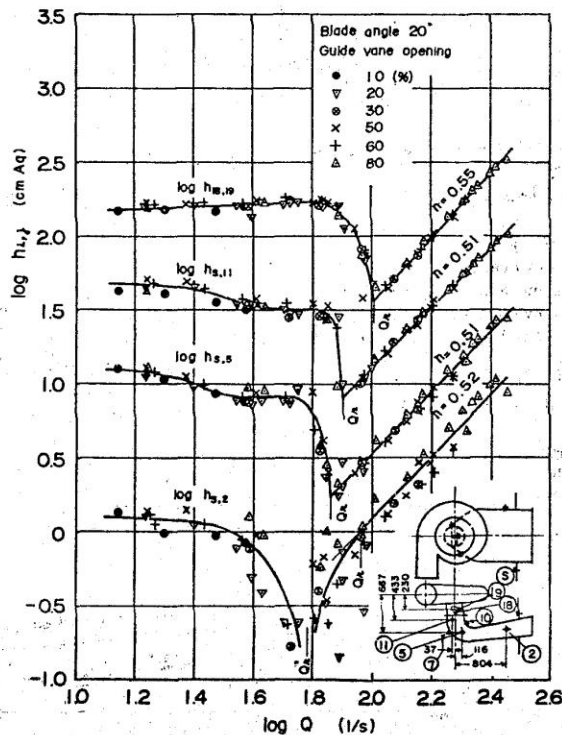


Fig. 5 Characteristics of draft tube index method applied to diagonal flow pump-turbine (C)

pressure between the pressure taps (2), (5), and (11) around the bending portion of draft tube and the pressure tap (s), and the pressure taps (18) and (19) at the blade angle of 20 deg. In this case also, $h_{i,j}$ was not influenced by the guidevane opening over the entire range of Q . The belly side $h_{s,16}$ showed the same characteristics also.

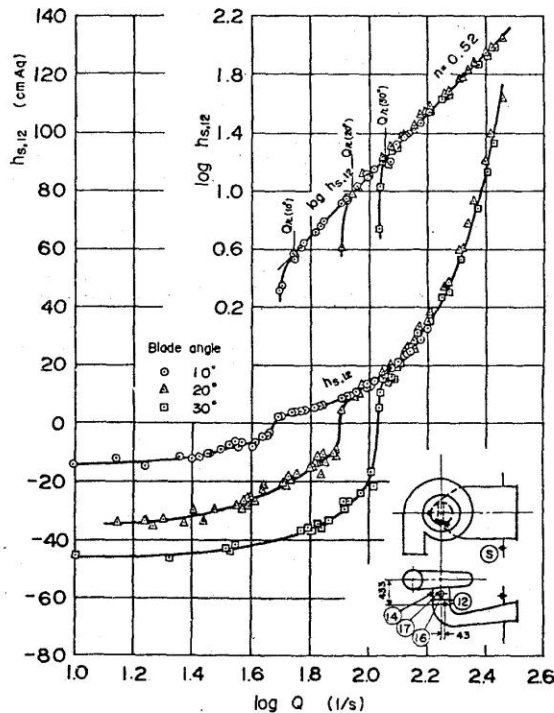


Fig. 6 Characteristics of draft tube index method applied to diagonal flow pump-turbine (C)

Fig. 6 shows the index characteristics of the differential pressure ($h_{s,12}$) between the pressure tap (12), around the downstream of the bending portion, and the pressure tap (s) at three different blade angles of 10, 20, and 30 deg and at different percentages of guidevane openings. At no blade angles is $h_{s,12}$ influenced by the guidevane opening as are the characteristics in Fig. 5. The beginning discharge of reverse flow is $\log Q_r$ (10 deg) = 1.74, $\log Q_r$ (20 deg) = 1.94, and $\log Q_r$ (30 deg) = 2.05. The same $Q \sim h_{s,12}$ relation remains independent of the influence of blade angle in a discharge range larger than the beginning discharge of reverse flow at each blade angle. The index characteristics of the differential pressure taps (14) and (s), and pressure taps (16) and (17) also showed the same tendency. In other words, this indicates that in the range of $Q > Q_r$, the index method is applicable to pump-turbines with the adjustable runner blades and the adjustable guidevanes. However, the back differential pressure $h_{s,7}$ showed an unfavorable index characteristic.

Relation Between Pressure Tap Location and Beginning Discharge of Reverse Flow. Fig. 7 shows how the ratio of the beginning discharge of reverse flow (Q_r) to discharge (Q_m) indicating maximum efficiency value— Q_r/Q_m —changed along the draft tube surface, by the ratio of pressure tap location (L) to the runner inlet diameter (d)— L/d . For this calculation, Q_m , the discharge at the maximum point of the efficiency envelope curve obtained by changing guidevane opening, was used for the Francis pump-turbine (B), and Q_m (10 deg), Q_m (20 deg), or Q_m (30 deg), as shown in Fig. 1, was used for the diagonal flow pump-turbine. It is difficult to determine the location of each pressure tap accurately because the draft tube was of complicated shape. In this case, the location of the pressure tap included in the plane vertical to the draft tube center axis was indicated by L ; length of center axis. However, the Francis pump-turbine (A) with fixed guidevanes was examined separately from Fig. 7, because discharge at maximum efficiency was relatively smaller than that of a pump-turbine with

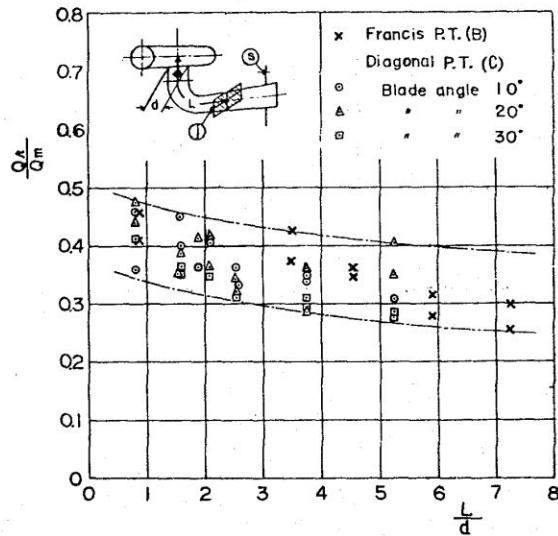


Fig. 7 Relation between the draft tube wall position and beginning discharge of reverse flow

adjustable guidevanes. As clarified by the figure, the relation between Q_r/Q_m and L/d remained almost the same in the two pump turbines; the smaller L/d was, or the closer pressure tap was to the runner, the larger Q_r/Q_m became.

Pressure Difference Along the Draft Tube Wall Surface. Fig. 8 shows a variation in the pressure difference ($h_{s,j}$) between the draft tube side wall and the suction tank against L/d in the case of the diagonal flow pump-turbine. In Fig. 8, the pressure difference ($h_{s,j}$) in the discharge range of $\log Q = 2.4 > \log Q_r$ displays almost the same degree of differential pressure when $L/d > 4$; but if $L/d < 4$, the differential pressure increases abruptly as L/d grows smaller. In the discharge range of $\log Q = 1.4 < \log Q_r$, however, $h_{s,j}$ shows the minimum when $L/d \approx 4$, and the maximum when $L/d \approx 2.5$; if $L/d < 2$, $h_{s,j} < 0$. In other words, concerning the differential characteristics of this pump-turbine, if one of the pressure taps was located on the draft tube wall surface ($L/d < 2$), $h_{s,j}$ became smaller than 0 in the discharge range of $Q < Q_r$. Data of the Francis pump-turbine (B) were very similar to those of the diagonal flow pump-turbine. When $L/d \approx 2.7$, $h_{s,j}$ became 0 (zero); when $L/d < 2.7$, $h_{s,j}$ became smaller than 0.

The value of L/d at which $h_{s,j}$ became 0 was, of course, related to reverse flow characteristics of the runner; moreover, this L/d was considered to be influenced even by the location and shape of the bending portion of the draft tube. Regarding the two types of pump-turbines with adjustable guidevanes used for this experiment, the value of L/d at which $h_{s,j}$ became 0 proved to be a position

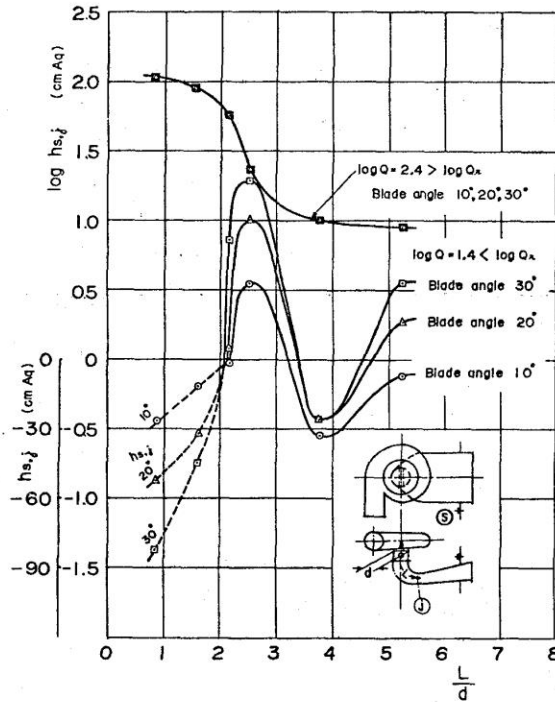


Fig. 8 Pressure difference along the draft tube wall surface of diagonal flow pump-turbine (C)

corresponding to approximately 70 percent of $\frac{L}{d}$ at the center of the bending portion of the draft tube.

Selection of Pressure Tap Location. The conditions required for the pressure difference characteristics of the pressure taps for index are as follows:

1 $Q = k \cdot h_{s,j}^n$ should be satisfied in as wide a discharge range as possible.

2 Indicated pressure difference should be as big as possible and as stable as possible.

3 The indicated pressure difference and discharge in the characteristics should be 1 versus 1.

To satisfy condition (1), as shown in Fig. 7, the larger are the pressure taps of the $\frac{L}{d}$ position, the smaller a beginning discharge

of reverse flow may be used. To satisfy condition (2), as shown in Fig. 8, the smaller the $\frac{L}{d}$ is, the better the results obtainable in the discharge range of $Q > Q_r$. To satisfy condition (3), as shown in Fig. 8, it was necessary to provide a pressure tap in the

range of $\frac{L}{d}$ in which $h_{s,j} < 0$ was insured in a discharge range of $Q < Q_r$. On assembling these three conditions, it can be stated that the required condition for location of a pressure tap was to provide it at a position where $h_{s,j}$ was smaller than 0 in the discharge range of $Q < Q_r$.

Conclusion

The applicability of the Winter-Kennedy method as an index method for reversible pump-turbines under pumping operation has been experimentally examined; as a result of this examination, a method called a draft tube index method has been investigated. The following conclusions have been deduced from these examinations and experiments:

1 When the draft tube index method is applied in a discharge range exceeding the beginning discharge of reverse flow (Q_r), there is a relation of $Q = k \cdot h_{s,j}^n$ between the discharge (Q) and the indicated pressure difference ($h_{s,j}$). This relation is practically independent of the type of pump-turbine, guidevane opening, and blade angle. It has an ideal characteristic as a relative discharge.

2 In the discharge range of $Q < Q_r$, pressure differences between one pressure tap located on the draft tube wall, which is the range of approximately 70 percent of $\frac{L}{d}$ at the center of the bending portion of the draft tube, and another pressure tap located on the fully upstream side of the bending portion, and between two pressure taps located on the air pipe near the draft tube wall, have been proven to be negative values (-). Under this condition, there is a relationship of 1 versus 1 between the discharge and the pressure differences.

3 The location of the pressure taps for the Winter-Kennedy method must be carefully selected. This pressure tap location is different from that which insures satisfactory results during turbine operation. In a diagonal flow pump-turbine, variation in the measuring points is very wide, considerably influenced by the guidevane opening and the blade angle; therefore, in this case, a very careful examination must be performed from a precision standpoint before starting practical operation.

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