532.574.8:627.13:543.257

Flow Measurement of Water Turbine by Means of Salt Dilution Method*

By Tatu ITAYA**, Toshio TAKENAKA***, and Tsuyoshi HATTORI****

About ten years ago, the authors devised the method to measure the flow rate of the water turbine by seeking the rate of dilution of the water discharged from the turbine, by measuring its electric conductivity. And after improving the apparatus, the rate of dilution became to be measured to the degree of 10^{-7} , and the water temperature, which had an important effect on the measurement of the electric conductivity, to the accuracy of $1/100^{\circ}\text{C}$. Then, from the year 1954 to 1958, we carried out the flow measurements of rivers and several power stations, the capacities of which were $1\sim 27\text{ m}^3/\text{sec}$, with effective results.

1. Introduction

The principal purposes of flow measurement of water turbine are (1) efficiency measurement of the water turbine and (2) determination of the time to repair the runner from the economic standpoint. For these purposes, recently, the accuracy of the flow measurement of the water turbine in power plants has been taken up seriously, and each electric power company frequently carries out comparison tests of several methods for the flow measurements and many methods are studied from various points of view. However, it has not been decided yet which method is the most accurate. Among them the salt dilution method seems to be one of the ideal methods because there is no need to add anything to the equipments of the power station, and there is no power loss by stopping the turbine, and the treatment is comparatively simple and economical. However, as it is well known, since the old salt dilution method was to measure the diluted consistency chiefly by means of chemical analysis⁽¹⁾⁽²⁾, the test was complicated and took much time and the accuracy was low, and much salt was consumed.

About ten years ago, the authors devised the method to measure the flow rate of the water turbine by seeking the rate of dilution***** of the water discharged from the turbine by measuring its electric conductivity. And after improvement of the apparatus, it has become possible to measure the rate of dilution to the accuracy of 10^{-7} , and

the water temperature, which has an important effect on the measurement of electric conductivity, to that of $1/100^{\circ}\text{C}$. And from 1954 to 1958, the authors carried out flow measurements of rivers and several power stations whose capacities were 1 to $27\text{ m}^3/\text{sec}$, with effective results. However, as the international standard of the flow measurement of the open channel by means of the salt dilution method***** is to be established in near future, the authors take out their old paper, and give the outline of the principle, apparatus and the operation of their method, reporting some examples of tests.

2. Principle of salt dilution method

The principle of the salt dilution method is as follows: Saturated salt water is poured continuously into the upper-stream at a constant rate, and the electric conductivity of the diluted water is measured at the down-stream where it is mixed thoroughly; thus the rate of dilution is determined, and therefrom the flow rate is calculated.

Fig. 1 is an explanatory diagram of this method. When the saturated salt water, poured from the upper reservoir or the mid point of penstock at a constant rate $q\text{ cc/sec}$, is diluted with the flow of the water turbine $Q\text{ m}^3/\text{sec}$, the rate of dilution K becomes

$$K = q \times 10^{-6} / (Q + q \times 10^{-6}) \approx q \times 10^{-6} / Q$$

Accordingly, the flow rate of the water turbine is given by

***** It is the ratio of the poured saturated salt water to the water passing through the water turbine.

***** Draft ISO Recommendation No. 592-Liquid Flow Measurement in Open Channels Dilution Methods for Measurement of Steady Flow, Part 1-Constant Rate Injection Method.

* Received 16th October, 1963.

** Professor, Tokyo Institute of Technology, Meguro-ku, Tokyo.

*** Assistant Professor, Tokyo Institute of Technology.

**** Vice Sect. Chief, Japan Zeon Co., Ltd.

$$Q = \frac{q}{K} \times 10^{-6} \text{ m}^3/\text{sec} \quad (1)$$

Next, when the temperature of the water is $t^\circ\text{C}$ and the electric conductivity (the reciprocal of electric resistance) is $\lambda_{K,t}$, the following linear relation holds between $\lambda_{K,t}$ and $K^{(3)*}$:

$$\lambda_{K,t} = \lambda_{0,t} + aK \quad (2)$$

where $\lambda_{0,t}$ is the electric conductivity of natural water (river water) at the temperature $t^\circ\text{C}$, and a is a constant to give the inclination of $\lambda_{K,t} \sim K$ line.

Moreover, it was experimentally ascertained that in this range, when $K = \text{constant}$, the electric conductivity changes linearly with the temperature; that is, if the temperature of the solution changes from $t^\circ\text{C}$ to $(t + \Delta t)^\circ\text{C}$, $\lambda_{K,t}$ becomes

$$\lambda_{K,t+\Delta t} = \lambda_{K,t}(1 + b \cdot \Delta t) \quad (3)$$

in which b is the constant.

3. Apparatus

3.1 Apparatus for pouring salt water

As shown in Eq. (1), the measuring accuracy of the flow rate of the water turbine depends on

Fig. 1 Salt dilution method

Fig. 2 Apparatus for pouring salt water (Part 1)

the measuring accuracy of q and K . When the value of q is large, K becomes large, and the measuring accuracy of Q is higher. In the authors' case, however, considering the gross quantity of the salt, etc., the flow rate of the pouring salt water q was set at $K = 30 \sim 60 \times 10^{-6}$. When the flow of the water turbine Q , and accordingly q of it, were small, salt water was poured at the inlet of the penstock, utilizing the head of salt water itself shown in Fig. 1. Within $Q = 5 \text{ m}^3/\text{sec}$, this method can be applied. However, when the flow rate is larger than the above, a pump is used to push the salt water as shown in Fig. 4.

Fig. 2 and Fig. 3 give the apparatus of pouring salt water under its head. With Cock C_1 adjusted in such manner as to keep the water level in Tank T_2 always constant, the salt water is poured at a constant rate, through a funnel and a rubber hose. The approximate value of q is read with a Venturi-meter at the outlet of the Tank T_2 , but the accurate value of q is given by measuring the time when the water level fell from some height in Tank T_1 .

Fig. 3 Apparatus for measuring and pouring salt water into the inlet of the penstock

Fig. 4 Measuring tank and pump for injecting salt water into the penstock (Part 2)

* According to the authors' study, in the range of more than $K = 3 \times 10^{-4}$, the linear relation of Eq. (2) does not hold.

Fig. 5 Measuring tank and pump for injecting salt water into the penstock

Fig. 6 Injection pipe setup

Fig. 7 Injection pipe set up on the wall of the penstock

with a stop-watch.

Fig. 4 and Fig. 5 show the pouring apparatus with a pump at Ooigawa Power Station. The apparatus was set up on a viaduct, about 70 m upstream from the power house along the penstock, for the convenience of carrying weight cargos. As the water pressure in the penstock at this spot was about 6 kg/cm^2 , 4-stage, 8 kg/cm^2 Turbine Pump 50 mm in diameter was used to send the salt water. In this figure, $T' \sim T''''$ are drums used for solving salt and keeping the salt water supply. Two bags (40 kg for one bag) of salt were consumed to make one drum (200 l) of saturated salt water. T is a tank made by welding one and a half drums, and has a level meter on one side. By reading a scale of the level meter and the time required for a falling of the water level, the pouring rate q is given. By opening the Cock V_3 fully, which is usually closed, and observing the rotameter F , the opening of valve V_2 is adjusted beforehand when salt water turns back to Tank T through Cock V_4 .

Fig. 6 and Fig. 7 show the apparatus for salt water injection tube, devised to pour the salt water in the penstock. By using such an apparatus, the pouring tube can be set or removed without stopping the turbine.

Kohlrausch bridge

Electric resistance of electrodes r
 Electric resistance of thermistor r_{th}
 In equilibrium of bridge $r = (r_1/r_2)R$
 $r_{th} = (r_1/r_2)R_{th}$

Fig. 8 Apparatus for measuring electric resistance

Fig. 9 Kohlrausch Bridge for measuring electric resistance of diluted solution

3.2 Apparatus for measuring electric resistance

In Fig. 8 and Fig. 9 is given the apparatus for measuring electric resistance, consisting of an oscillator, amplifier, Kohlrausch-bridge and electrode. Alternating-current was used for the electric source of the Kohlrausch-bridge to avoid polarization of the salt water. The alternating-current oscillator (about 1 000 cycles, output voltage 0~25 volt.) and the amplifier (to amplify and rectify the unbalance of the bridge and to move the direct current ammeter) was housed in a box for the convenience of carrying, and for the variable resistor of the bridge, a platinum wire was used, as joined to a bakelite plate, in a semi-circle of 30 cm in radius. As the standard resistance, several kinds of resistances of manganin wire had been provided beforehand, which is almost equivalent to the electric resistance of the river water being connected to the bridge in the field test.

For the electrode, the following two kinds were used: the first one, shown in Fig. 10 (a), is two spiral platinum wires 1 mm in diameter, faced at the distance of about 1 cm. This was used in the first stage of the tests, to measure the electric resistance of the water drawn in beakers (300 or

500 cc) from the tailrace. The second one shown in (b) is used to measure the electric resistance of the water by soaking it in the tailrace, and the inside electrode is a spiral 10 mm in diameter and 40 mm in length (seven and a half rolls of silver wire plated with platinum), and the outside is a cylinder with many holes, 30 mm in diameter and 80 mm in length (silver plate, plated with platinum), and they are covered with a hard vinyl tube with many holes.

3.3 Apparatus for measuring water temperature

Electric resistance of diluted salt water varies remarkably with temperature. So, for the measurement of the temperature sufficient accuracy should be assured. Moreover, for the sake of speedy measurement and remote measurement, a thermistor was used, and in this case, the above apparatus to measure electric resistance was available as it was; by simple operations of converting to the thermistor circuit with Switch S_1 in Fig. 8, and at the same time, to the standard resistance R_{th} with Switch S_2 , the thermistor resistance r_{th} can be measured. The thermistor is, as shown in Fig. 10, put on a part of the electrode holder. Fig. 11 gives the characteristic of the temperature vs. electric resistance of the thermistor; in the temperature range of 15 to 22°C, the resistance variation with the temperature variation of 1°C is 3.5 to 5%. Therefore, with the above mentioned apparatus, the temperature variation of 1/100°C can

Fig. 10 Electrode

Fig. 11 Temperature vs. thermistor resistance

Fig. 12 Temperature vs. electric conductivity

be detected.

4. Preliminary experiments

4.1 Determination of coefficient of temperature correction

By changing the temperatures of samples of water in the channel ($K=0$) and diluted salt water with several consistencies in a beaker or a bucket, and measuring the electric resistance, the electric conductivity $\lambda_{K,t}$ vs. water temperature t curve is drawn. Fig. 12 shows an example of the $\lambda_{K,t} \sim t$ curve of salt solution with various values of K ; it is seen that $\lambda_{K,t}$ and t at a constant K are in a linear relation. So, by seeking the gradient of this straight line $(\lambda_{K,t+\Delta t} - \lambda_{K,t})/\Delta t$ in this figure, and dividing it by $\lambda_{K,t}$, the constant b is given.

4.2 Determination of constant α

Although the poured salt water is in saturated state and it should have almost the same consistency, depending on the degree of agitation in making the solution or on the length of the standing time, there may be a little unevenness. So, the

Fig. 13 Rate of dilution vs. electric conductivity

salt water used in each test was sampled in test-tubes, and during the time of converting the generator load, solutions of $K=0 \sim 60 \times 10^{-6}$ were made in every test. Then, by seeking the value of each $\lambda_{K,t}$, and correcting the temperature, $\lambda_{K,t} \sim K$ diagram for a certain temperature was drawn, and from the gradient of it the constant α was given. Fig. 13 is an example of $\lambda_{K,t} \sim K$ diagram.

5. Test results

The tests of flow measurement were carried out eight times at five power stations and a mountain stream as shown in Table 1. The first five power stations had comparatively small head and flow, and were suitable for carrying out the authors' method. Based on the experiences of these tests, the apparatus and the test methods have been improved.

The followings are the test results at three power stations.

5.1 Susukikawa Power Station

At this power station, the comparison tests of eleven kinds of methods to measure the flow of

Table 1 Test places

No.	Date	Name of power station	Output of water turbine kW	Head m	Dis-charge m ³ /sec	Type of water turbine
1	1954-2	Oshino	1 103	39.9	2.62	Francis
2	1954-8	Kuroda	520	45.9	2.18	"
3	1954-10	Kuroda	520	45.9	2.18	"
4	1955-3	Oshino	1 103	39.9	2.62	"
5	1955-6	Susukikawa	430	38.5	1.16	"
6	1957-3	Yugawa	—	—	0.2	Mountain stream
7	1957-6	Arakawa	3 500	122.4	3.20	Francis
8	1958-5	Ooigawa	23 500	112.7	22.7	"

Table 2 Test results (Susukikawa P.S.)

Test No.	Test time hr-min	Gener- ator load kW	Upper reservoir			Water at tail race						Dis- charge Q m ³ /sec	Dis- charge of weir Q_w m ³ /sec	$\frac{Q-Q_w}{Q_w}$ $\times 100$ %
			Level decre- ment of tank T ₁ h cm	Meas- uring time of tank level T sec	Pouring dis- charge of salt water q cc/sec	Electric resistance k Ω	Mean value of electric resist- ance r k Ω	Electric conduc- tivity λ 1/k Ω	Electric resist- ance of therm- istor r_{th} k Ω	Tempe- rature of water t °C	Rate of dilu- tion K $\times 10^{-6}$			
1	17-41	109.7	4.0	146.4	19.32	1.848 1.845 1.855 1.855 1.845	1.848	0.541	27.73	16.20	42.9	0.450	0.449	0.22
2-1	17-58	204.5	14.0	372.0	26.55	1.908 1.906 1.900 1.904 1.904 1.908	1.904	0.525	27.73	16.20	38.3	0.693	0.694	-0.20
2-2	18-09	205.1	12.0	271.4	31.20	1.826 1.820 1.813	1.820	0.549	27.73	16.20	45.3	0.689	0.696	-0.95
3-1	18-17	303.4	14.0	274.2	36.10	1.900 1.908 1.906 1.906 1.906 1.906	1.906	0.525	27.73	16.20	38.3	0.945	0.937	0.85
3-2	18-28	303.3	15.0	270.8	39.10	1.853 1.863 1.857 1.867 1.853	1.860	0.538	27.73	16.20	42.1	0.929	0.937	-0.85
4-1	18-37	400.0	18.0	279.0	45.60	1.920 1.920 1.924 1.920 1.924 1.920	1.920	0.521	28.10	15.92	38.2	1.195	1.183	1.01
4-2	18-50	402.5	16.0	239.2	47.25	1.902 1.902 1.900 1.898 1.895 1.900	1.900	0.526	28.20	15.85	39.9	1.185	0.191	-0.50

(Note: Cross area of tank T₁ for pouring salt water=706.0 cm²)

water turbine, such as Pitot tube method, orifice method, Gibson method, etc. were carried out utilizing the discharge of weir. The straight channel, made of reinforced concrete, was 2.50 m in width and 11.00 m in length, and at the end of the down stream, there was a suppressed weir whose crest was 1.00 m high.

Fig. 14 Comparison of weir method with this method (Susuki-kawa Power Station)

Fig. 15 Variation of electric conductivity with time (Ooigawa Power Station)

Fig. 16 Variation of electric conductivity with time (Arakawa Power Station)

Fig. 17 Output of generator vs. discharge of water turbine (Ooigawa Power Station)

The tests of this method were repeated two times for every 100 kW between 100 kW and 400 kW of generator load. The results are given in Table 2. For this test, only one bag (40 kg) of salt was consumed.

The comparison of this result with the weir discharge Q_w is shown in Fig. 14; the measuring points are scattered, but the average value (the line in the figure) is $\pm 0.5\%$ maximum, and well coincides with the weir discharge.

5.2 Ooigawa Power Station

The test was carried out generally three times for every one of seven loads between 10 000 kW and 22 800 kW, and 45 bags (40 kg per one bag) of salt were consumed.

Fig. 15 gives the variations of the electric conductivity of the tail race water with time. In the above test, the value of $\lambda_{K,t}$ during the pouring of salt water had always been almost constant, as shown in Fig. 16, but in this test, as shown in Fig. 11, the value of $\lambda_{K,t}$ fluctuated. So, by measuring the area of the $\lambda_{K,t}$ curve (the shaded portion) with planimeter, the average value was given. The relation between the discharge of the water turbine and the output of the generator is shown in Fig. 17.

5.3 Yugawa river

This is the result of the flow measurement at a mountain stream in winter. The distance between the measuring spots was 50 m where a proper number of cascades and a few currents and stagna-

Fig. 18 Sketch of stream

Fig. 19 Variation of electric conductivity with time (Yugawa)

Table 3 Test results (Yugawa)

Test No.	Test time hr-min	Upper stream					Down Stream				Discharge Q m ³ /sec
		Pouring time of salt water min	Level decrement of tank T ₁ h cm	Measuring time of tank level sec	Mean value of measuring time T sec	Pouring discharge of salt water q cc/sec	Electric conductivity fore and after pouring of salt water λ_0 1/k Ω	Electric conductivity during pouring of salt water λ 1/k Ω	Temperature of water t °C	Rate of dilution K	
1	15-42	21.0	10.0	357.0 357.3 357.4	357.2	19.79	0.573	0.787	0.2	$\times 10^{-6}$ 99.5	0.199
2	16-33	18.5	10.0	298.3 297.3 296.3	297.3	23.78	0.573	0.831	0.2	120.5	0.197
3	17-23	10.0	10.0	258.0 259.2	258.6	27.34	0.573	0.869	0.2	137.5	0.199

Note: Cross area of tank T₁ for pouring salt water=706.0 cm²

tions existed and they seemed to be enough for agitating the salt water. Fig.18 is a sketch of this mountain stream.

The stream water was sampled at intervals of 30 seconds after beginning to pour salt water to measure the electric resistance. The variation of the electric conductivity with time is given in Fig. 19, which shows that the dilute condition becomes steady about 10 minutes after the beginning of pouring salt water. The calculated values of the discharge of the stream are shown in Table 3.

6. Conclusions

6.1 Water turbine of small capacity

The test results were generally good as seen in the example of Susukikawa Power Station; values of electric resistance coincided for several measurements within 1%, and considering the error of the pouring quantity q , the error of the discharge Q seems to be about $\pm 1.5\%$. When the flow rate is at such a degree, the apparatus is inexpensive and the test is simple. So, this method will prevail in future.

6.2 Water turbine of large capacity

In this case the principle and method of

measurement are the same as the case of the small capacity. However, the capacity of the apparatus of pouring salt water becomes large. If this apparatus is designed successfully, the above accuracy will be assured.

6.3 River

In Yugawa, very good results were produced. The open channel with a mountain stream with irregular forms which would be unsuitable for other methods seems to have been favourable. The measuring course should be taken long enough, or the flow should be disturbed artificially.

The authors wish to express their thanks to the Tokyo, Chubu, Kansai and Tohoku Electric Power Companies, Water Turbine Section of Central Research Institute of Electric Power Industry and Civil Department of Yamanashi Prefecture, for their kind cooperation in this study and the field tests.

References

- (1) B.F.Groat: *Trans. ASCE*, Vol.80, No.1 366 (1916), p. 1.
- (2) e.g., I. Oki: *Experimental Method for Hydraulic Machinery*, (1933).
- (3) J. Sameshima: *Experimental Method for Chemistry*, (1944).