FLOW MEASUREMENT IN HYDROELECTRIC STATIONS USING TRACER DILUTION METHOD – CASE STUDIES

U. Muthukumar
Senior Research Engineer,
Fluid Control Research Institute,
Palakkad, Kerala

Jacob Chandapillai
Head,Center for Water Management
Fluid Control Research Institute
Palakkad, Kerala

S.Saseendran
Director,
Fluid Control Research Institute
Palakkad, Kerala

1. INTRODUCTION

A large number of hydroelectric power stations, both large and small are being built and commissioned in India by public as well as private agencies. Field Efficiency testing of the hydraulic turbines in these stations is performed to determine the efficiency of the turbine and compare it with the guaranteed values given by the supplier. Similar tests are also being carried out in existing installations mainly to understand the performance. Various methods as outlined in the IEC standard are available for field efficiency testing of hydraulic turbines. High cost of performing the test and difficulties in performing the test are some of the factors restricting the test.

The actual flow measurement remains the big challenge to overcome at the site for field efficiency testing of turbines, especially in plants where provisions for flow measurement has not been made or become unusable. Flow measurement using Tracer dilution has proven to be inexpensive, accurate and adaptable (Cyrenne P.Eng .M, 2002) and has been considered as a cost effective method suitable for a variety of applications including large discharge pipelines and for flow measurement in sewer lines (Gutierrez F. Alberto, 1983).

This paper discusses two cases where tracer dye dilution technique was used to measure the flow rate in penstock for hydroelectric power plants and the experience shared.

2. TRACER DILUTION TECHNIQUE FOR FLOW MEASUREMENT

Two methods outlined in standard (ISO 2975-1), known as constant rate injection method and the integration (sudden injection) method are based on the dilution principle for flow measurement used for field efficiency testing of Hydro turbines. Flow measurement in pipelines using Tracer dilution involves injecting the tracer dye of known concentration into the water pipeline, allowing a sufficient length of pipe for mixing of the tracer with water and then sampling the water for the dye concentration. The dilution of the dye concentration gives a measure of the water flow in the pipeline.

Of the two methods, Constant rate injection method is more suitable for flow measurement due to the practical difficulties of the Integration method such as weighing the exact amount of dye injected into the stream, finding exact volume of the stream between injection point and sampling point and requirement of multiple instruments for sampling.

2.1 Principle

The principle of the constant-rate injection method is the continuous injection of a tracer into the main water flow at a steady measured rate and the determination of the resulting concentration of tracer, relative to its initial concentration, at a point far enough downstream to ensure thorough mixing. The discharge Q can be determined from $Q = q\frac{C_1 - C_2}{C_2 - C_0}$ where Q is the discharge to be measured, q is the

discharge of the injected tracer solution, C_0 is the initial concentration of tracer in natural water, C_1 is the concentration of tracer in the injected fluid and C_2 is the concentration of tracer at the sampling location

2.2 Procedure and Equipment Required

The procedure for the flow measurement involves Dye injection and Dye sampling. Rhodamine WT can be used as the dye as it is water soluble, harmless, highly detectable, inexpensive and reasonably stable. Dye Injection is done at the Dye injection location determined based on site conditions. The process involves injecting unit concentration of the Rhodamine WT dye into the main flow in the penstock using a constant rate injection pump. The flowrate can also be measured by weighing the quantity of dye injected for a time period or by noting change in volume in the volume jar from which the dye was pumped for a particular time. Concentration of dye at the dye sampling location can be determined as per site conditions using a calibrated Turner designs AU10 fluorometer. The sampling may be done using the straight through mode where the sample water is directly passed through the fluorometer or by collecting the sample and then pumping the sample using a immersible pump through the fluorometer.

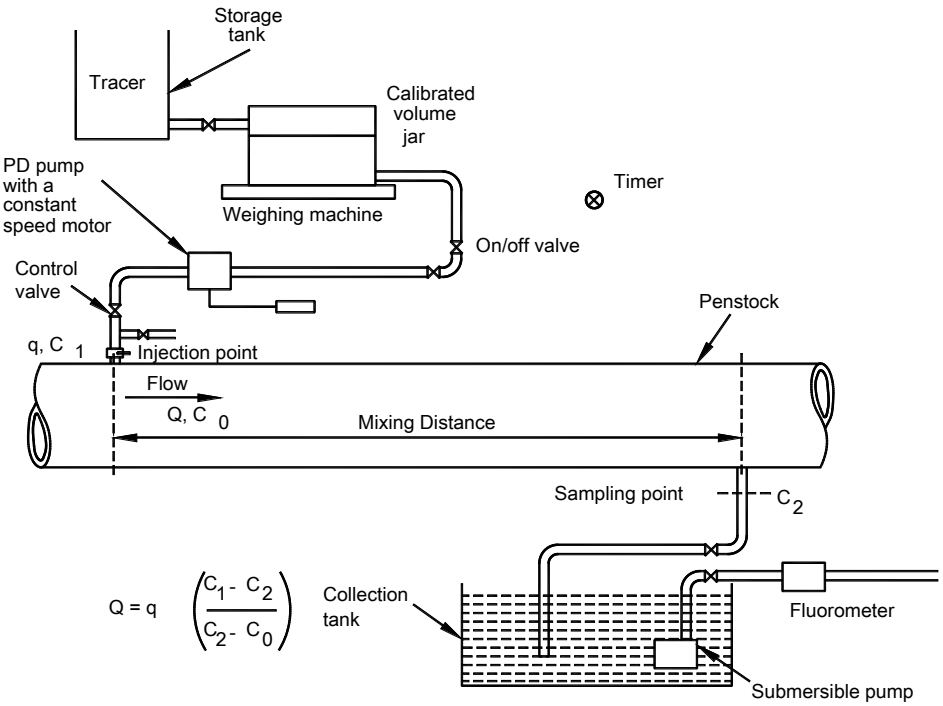

Fig.1 Schematic of Test setup for case1

2.3 Site Requirements

The method requires that the dye mixing should be uniformly and evenly distributed across the sampling section, indicating a homogeneous mixing. There should be no dead pockets and no flow diversion between the dye injection and sampling location. The penstock tapings for dye injection and sampling should be clean, choke free and leak tight. It is to be ensured that the concentration of the tracer in natural water is constant and is less than 15% of the concentration at the sampling point during injection of tracer. Prior to the flow measurement, the mixing distance required for the site has to be determined. Guidelines given in the standard ISO 2975 is used to determine the mixing distance. The duration of tracer injection and the injection flowrate were estimated to determine the amount of dye tracer required for the measurement. The injection flowrate was found by taking the flowrate in the Penstock as the rated flow of the turbine.

This paper discusses two case-studies where flow measurement using dye tracer dilution technique was used.

3. CASE STUDY 1

Flow measurement in the penstock diameter of 3.05m and a length of 17.88m for a vertical Kaplan turbine running at 214.3 rpm with a runner diameter of 2.8m was performed using the tracer dilution method (FCRI/TDT-06-1999).

3.1 Test Setup

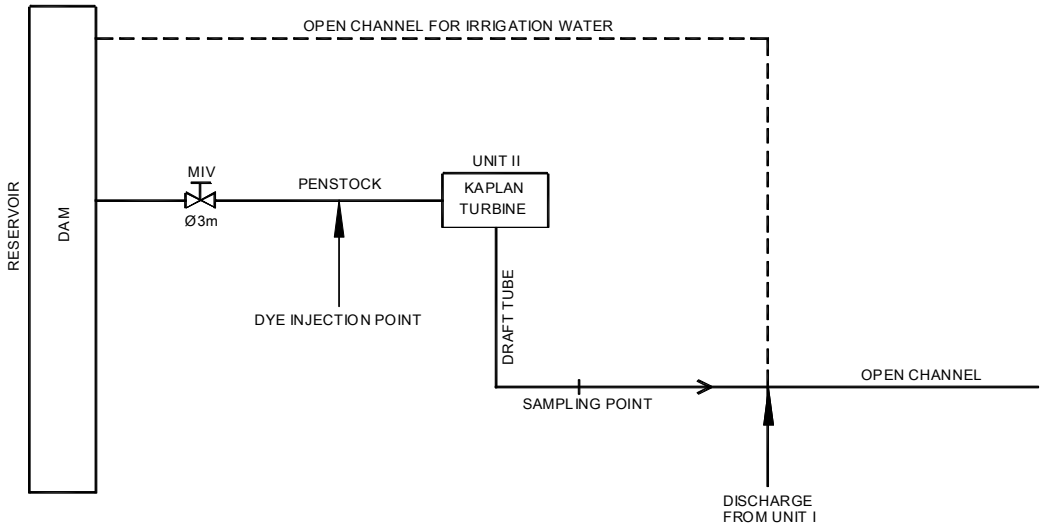

Fig.2 Schematic of Test setup for case 1

A schematic of the test setup is shown in Figure 2. Four pressure tappings were taken from the sides of the draft tube (downstream of the turbine) and these tappings were connected to a common header, from which samples were taken to the fluorometer. Even though there were four tapings which were connected to a common header, in the upstream of the turbine, these could not be made use for injection, since heavy leakage was found at many points. Hence a single point injection of the dye upstream of turbine was done in the test as shown in figure 3. As the flow rate expected through the turbine was around 40 cu.m/s, it was decided to inject the concentrated dye without dilution and adjust the injection flowrate so as to get a sample concentration of around 25 to 50 ppb.

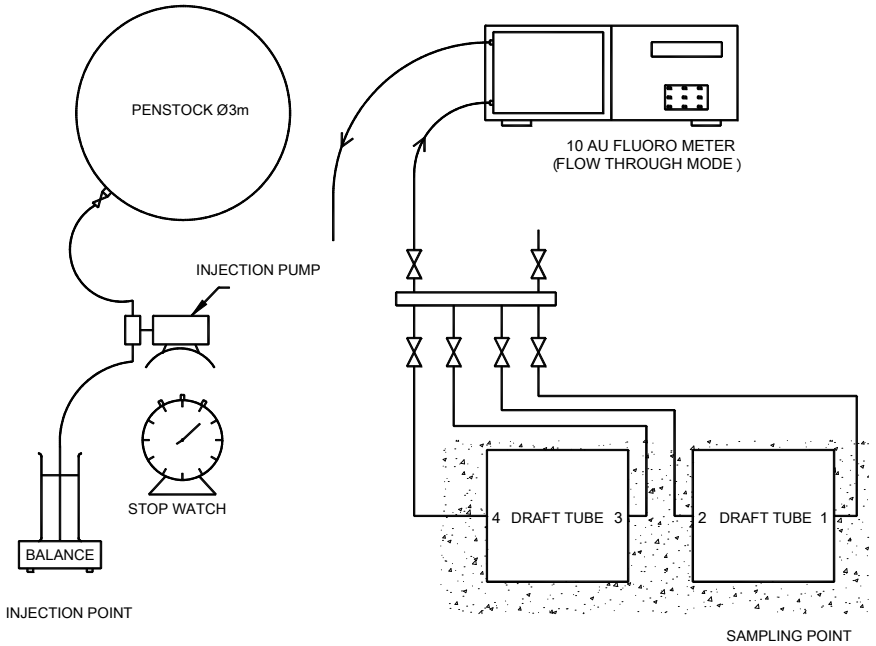

Fig. 3 Details of Injection and Sampling points for Case I

3.2 Calibration of fluorometer

The fluorometer was to be calibrated at 30 ppb before the commencement of actual dye injection. This is to enable the reading of the sample around 25 to 50 ppb. For this initially the fluorometer was blanked. This blanking was done using raw water from the penstock to pass through the fluorometer (flow through mode) and the concentration of any fluorescent material in the natural water at site was obtained (C_0). The concentration of the dye supplied by the manufacturers is considered as 'unity' for convenience. The absolute value of concentration of the dye is not necessary as the flowrate is determined by dilution ratio of the dye.

As the concentration of the sample expected downstream of the turbine is between 25 to 50 ppb, it was decided to calibrate the fluorometer at 30 ppb to pick the sensitivity range for the fluorometer. For this a standard solution was prepared with a concentration of 30 ppb (considering initial concentration as unity). Using a 500ml volumetric flask, 50ml of the concentrated dye was diluted with 4950m of water to get 10 was repeated progressively to get 100 ppb. Then 3 liters of the 100 ppb solution was diluted with 7 liters of water to get 30 ppb standard solution. During the dilution process, single 500ml flask was used for measurement of initial solution as well as addition of further quantity of water. Hence the concentration of the final solution is obtained accurately. The calibration of the fluorometer was carried out using a sample of known dilution of the dye called as the standard solution. Extra care was taken to prepare this standard solution so that error in preparation/dilution is reduced to a minimum.

3.3 Dye injection

After flushing the tube and injection pump with the injecting dye, the suction side tube of the injection pump was slowly put inside the initially weighted volume jar with dye. Then the pump was switched on and a stopwatch was started simultaneously. When the diluted dye reached the sampling point fluorometer showed the corresponding reading. After getting a stable reading, readings were recorded. When the necessary readings are recorded dye injection was stopped by switching off the injection pump and the stop watch was also stopped. The final weight of the flask with dye and the time taken to inject the dye was recorded. From this injection flowrate was determined. The dye injection rate should be fixed approximately to a desired level using the adjusting knob in the injection pump. The actual injection rate was found out during the actual test by gravimetric method and varied between 0.7 to 1.06 cc/s.

3.4 Sampling

Diluted samples are collected from the draft tube. As the surroundings of the draft tube is embedded in concrete, samples are collected through the pressure tapping already provided. As shown in figure 2, the draft tube is divided into two compartments and four pressure tappings are taken from the vertical wall. The four pressure tappings are brought to the valve chamber using 0.5 inch pipes and are connected to a common header which is then connected to the fluorometer using a flexible hose. Due to downstream pressure, there was sufficient flow through the fluorometer. The measurements were made in flow-through mode.

After injecting the dye in the upstream side, fluorometer readings were closely observed. When the dye reaches the sampling point, some quantity will reach the fluorometer through the pressure tapping and the header, when a stable reading is reached in the fluorometer, readings are recorded. Due to blanking of fluorometer C2-C0 is directly read from the fluorometer.

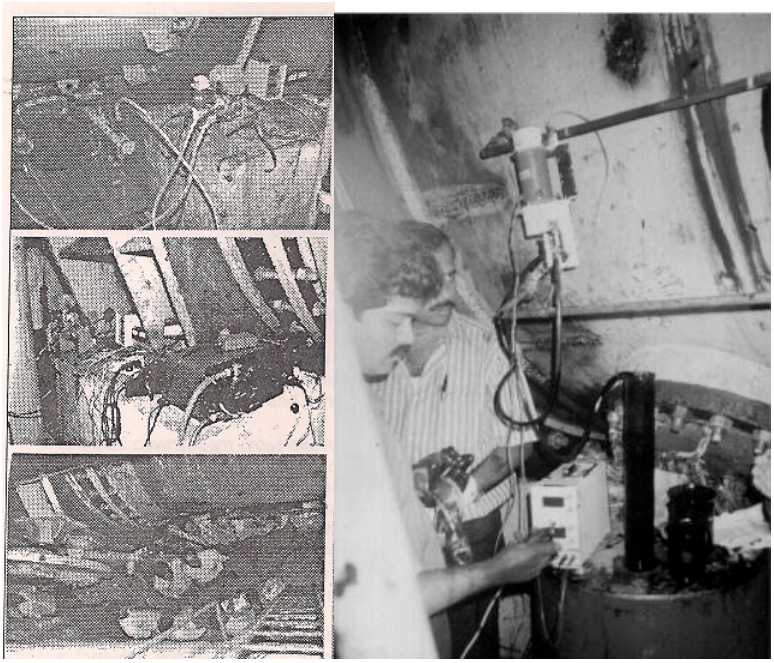

Fig 4. Photographs of the dye injection and sampling locations for Case1

3.5 Observations

During the actual site test, observations were made at six different load/flow rates. The flowrate was calculated based on the formula given earlier.

Table 1 Flowrate measurements for different loading conditions.

% Loading	Injection rate cc/s	Mean concentration value, ppb $C_2 - C_0$	Discharge m^3/s
106.4	1.066	26.42	40.34
101.4	0.977	27.28	35.8
79.6	0.979	34.48	28.13
71.5	1.059	36.64	28.91
49.8	1.067	51.68	20.65
43	0.724	38.48	18.81

3.6 Degree of mixing:

Dilution method is applicable only where the degree of mixing is within the tolerance limits. In order to ensure this, it is necessary to take different samples across the cross-section and determine the variation. In this site, it was not possible to have access to the tapping points. The only choice was to determine the concentration variation in the four tappings of the draft tube. An experiment was conducted to determine the same. While injecting from the injection points readings were obtained from each tapping points by closing and opening the valves provided in the tappings. Also one more reading was obtained keeping all the values in the open condition. This is the condition at which the actual efficiency tests were conducted. The results indicated a variation in the concentration at the draft tube as indicated in table 2.

Table 2 Dye Concentration in the tappings for Case 1

Tapping No.	Concentration (ppb)
1	0.92
2	1.1
3	2.15
4	7.2
All the above four	3.2

The degree of mixing estimated (ISO 9555 - 4) using the values of variation of dye concentration in the different tappings indicated that mixing was not sufficient and not within permissible limits as explained in 5.2.

4. CASE STUDY 2

Flow measurement in the penstock diameter of 5.75m and a length of 240 m for a vertical Francis turbine running at 214.28 rpm with a runner diameter of 4.1m was performed using the tracer dilution method (FCRI/TDT-15-2008).

4.1 Test Setup

The schematic of the test setup for the flow measurement is shown in Figure.4. Only one tapping was available at the upstream of the turbine and hence a single point injection of the dye upstream of turbine was done in the test as shown in figure 5. Four pressure tappings were taken from the sides of the

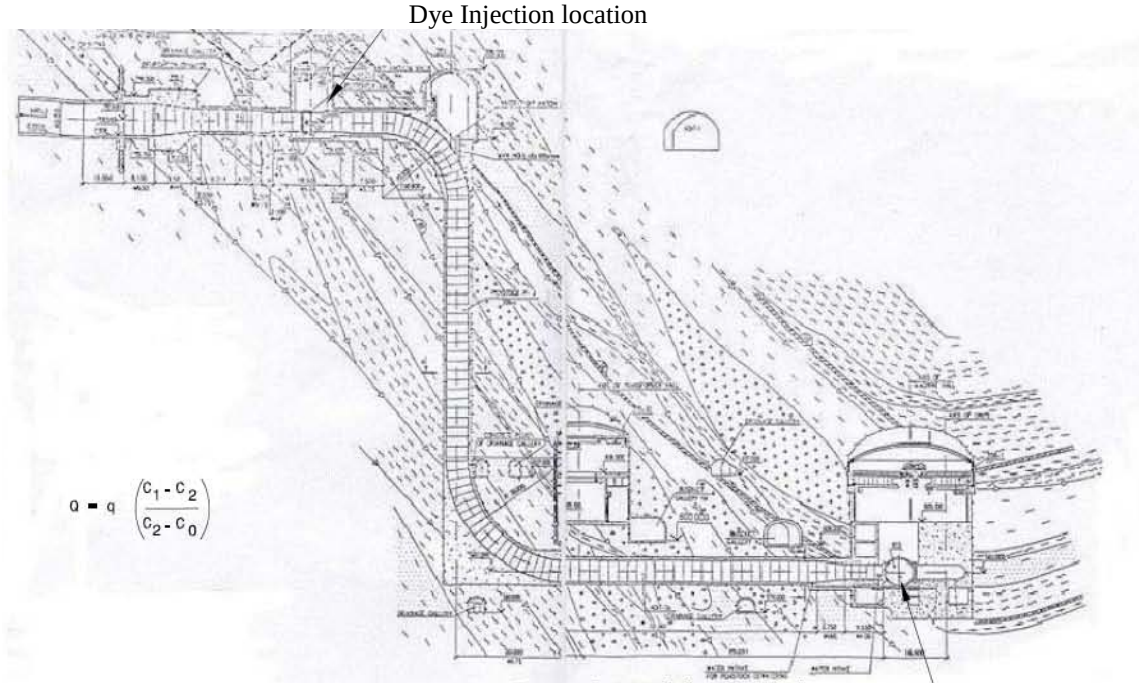

Fig 5 Schematic of Test Setup for Case 2

draft tube (downstream of the turbine) and these tappings were connected to a common header, from which samples were taken to the fluorometer. As sufficient pressure for continuous monitoring was not available in the common header when all four tappings were open, it was decided to shift the sampling point to the draft tube level measuring point. As the flow rate expected through the turbine was around 145 cu.m/s, it was decided to inject the concentrated dye without dilution and adjust the injection flowrate so as to get a sample concentration of around 50 to 75 ppb.

4.2 Fluorometer Calibration

Standard Solutions of Rhodamine WT Concentration were prepared at site with the water in the penstock in different concentrations by creating compositions. For this a standard solution was prepared with a concentration of 100 ppb (considering initial concentration as unity). Using a 500ml volumetric flask, 50ml of the concentrated dye was diluted with 4950m of water to get 10 ppt of mixture. 500 ml of this mixture was diluted with 4500 ml of water progressively to get 100 ppb. From this solution standard solutions of 66.67, 75 and 83.33 ppbs were made by appropriately diluting the 100 ppb solution.

During the dilution process, single 500ml flask was used for measurement of initial solution as well as addition of further quantity of water. Hence the concentration of the final solution is obtained accurately. The 100 ppb composition thus prepared was run through the fluorometer and a calibration run performed on it. Then the other standard concentrations of 66.67, 75, 83.33 ppb are run through the fluorometer to estimate the uncertainty of the fluorometer. The natural water in the penstock is then passed through the calibrated fluorometer and the default concentration of Rhodamine WT in natural water (C_0) is found to be 14.2 ppb.

4.3 Dye Injection:

Rhodamine WT of unit concentration (C_1) is injected into the penstock at the predetermined injection point at a constant flowrate (q) using appropriate pumps and mechanisms. The constancy of the flow rate of around 7.8 cc/s was checked by monitoring the change in weight of the tracer solution over a period of time.

4.4 Sampling:

The concentrations of Rhodamine WT in the sampling location is monitored continuously during the injection period and once the concentration reaches a constant plateau, reading for the concentration (C_2) are noted.

Dye Injection Location | Degree of Mixing Check Location | Sampling Location

Fig 6. Photographs of the dye injection and sampling locations for Case 2

4.5 Observations:

The turbine was run at four different loads and the sampling data obtained at the sampling location using the fluorometer was manually recorded. From the values of C_1, C_2, C_0 and q , the discharge through the penstock is determined. The dye concentrations as measured at the sampling points during the test at different loads as obtained from logged data are given in Table.3.

Table 3 Dye concentrations measured during different loadings of the turbine.

% Loading	Injection flowrate, cc/s	Mean concentration value, ppb C_2	Discharge, m3/s
100	7.8	67.7	145.76
85	7.9	75.53	128.45
75	7.9	83.16	115.24
60	7.8	96.42	94.89

4.6 Degree of mixing:

The degree of mixing was then determined shifting the fluorometer to the 2" taping location. The Dye Injection was continuously done and concentration from each of the four tapings measured individually. While injecting from the injection points readings were obtained from each tapping points by closing and opening the valves provided in the tappings. The results indicated a variation in the concentration at the draft tube as indicated in table 4.

Table 4 Dye Concentration at the tappings for Case 2

Tapping No	Mean concentration value, ppb, C_2
1	73.56
2	73.14
3	80.29
4	75.52

5. RESULTS & DISCUSSIONS

The accuracy and repeatability of the measurement depends on the mixing length available, the homogeneity in mixing and other site conditions such as the initial concentration of dye.

5.1 Mixing Length requirement

Both cases used single point dye injection at the pipe wall. The required mixing length as per the ISO 2975 standard works out to approximately 140 times the pipe diameter for an allowable variation of 2% in tracer concentration across the pipe conduit. Considering case 1, where a length of approx 5.9 times pipe diameter was available, with an addition of 100D for the turbine, the total mixing length work out to 106D approximately and this does not meet the requirement. Multi-point dye injection which requires reduced mixing length could not be used as the site conditions were not conducive.

Considering case 2, a length of 41.8D is available and when 100 D is added for the turbine, approximately 142D is available as mixing length, which was adequate as specified in the standard.

5.2 Degree of Mixing

Degree of Mixing (ISO 9555-1(1994)) is as given below.

Degree of Mixing, X = $$100\left[1-\frac{\sum_{i=1}^{m}\left|C_{2i}-\overline{C}_2\right|}{2m\overline{C}_2}\right].$$

Where C_{2i} - Mean dye concentration value (ppb) for tapping position i

$\overline{C}_2$ - Mean dye concentration value for all tappings

m - Number of tappings

Hence, degree of mixing works out to 55.57% for case 1 and 98.46% for case 2. As per the standard for good flow measurement accuracies, degree of mixing should be greater than 98%. For x greater than 90%, the expected error in flow can be calculated as 2 (100 – X) %. The error in flow works out to be too high for case 1 and 3.09% for case 2.

5.3 Dye Concentration in natural water

The initial concentration of rhodamine WT in the natural water was not noted in case 1 as the fluorometer was calibrated blanked. In case 2, the initial concentration was 14.2 ppb which exceeded the 15% limit specified in standard (IEC-41- 1991) in three loading conditions.

6. CONCLUSIONS

Based on the site conditions in both cases, Dye Tracer dilution method was used for flow measurement. The experience in using the technique in such conditions was discussed. From the case studies, the following are observed.

1. The Dye tracer dilution technique can be used successfully for flow measurement in cases where other methods are not feasible.
2. Standard guidelines with respect to the mixing length requirement for a single point injection with an error in mixing of around 2 % almost matched the case 2 where the error in mixing came around 3%.
3. The standard requirement that the initial concentration of the dye in natural water should be less than 15% was not met in case 2, but still the measurement was within permissible limits because of good mixing.
4. From the experiences at both sites, it is suggested that suitable provisions need to be made during the construction stage itself for injection of the dye and collection of the mixed solution ensuring accessibility to the tappings, otherwise it is difficult or sometimes impossible to ensure accurate flow measurement

7. ACKNOWLEDGEMENT

The authors wish to thank the authorities associated with the Hydoelectric power stations where these tests were performed.

8. REFERENCES

1. IEC- 41 1991 standard for Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbines.

2. ISO 9555 part 1 – 1994 Measurement of liquid flow in Open channels – Tracer dilution methods for the measurement of steady flow – General.

3. ISO 9555 part 4 – 1992 Measurement of liquid flow in Open channels – Tracer dilution methods for the measurement of steady flow – Fluorescent tracers.

4. ISO 2975– 1974 Measurements of water flow in closed conduits- Tracer Methods - Part 1:General.

5. ISO 2975– 1975 Measurements of water flow in closed conduits- Tracer Methods - Part 2:Constant rate Injection method using non-radioactive tracers.

6. Cyrenne P.Eng .M, 2002, Flow Measurement Using the Dye Dilution Technique, IGHM 2002 International Conference, Toronto.

7. Gutierrez F. Alberto, Siu Mankay, 1983, Flow measurement in sewer lines by the dye dilution method, Journal (Water Pollution Control Federation), Vol. 55, No. 5, pp. 531-535 Published by Water Environment Federation

8. FCRI/TDT-06-1999- FCRI Project Report on Flow measurement using Fluorescent Tracer Dilution Technique.

9. FCRI/TDT-15-2008 - FCRI Project Report on Field Efficiency, pressure pulsation and Index testing.

BIO DATA

U. Muthukumar graduated in Mechanical Engineering from the Madurai Kamaraj University in 1990. He started his career in Fluid Control Research Institute and from 1993 to 1999 he has worked in testing calibration of flow products and development of software for Valve/flowmeter selection and sizing. From 2000 he is working on projects involving Field Efficiency Testing of Hydroelectric turbines, design of pumps and testing of flow products.

Jacob Chandapillai graduated in civil Engineering from the University of Kerala in 1983. He obtained M.Tech in Civil Engineering from IIT, Madras. From 1985 to 1988, he worked for Tata Consulting Engineers, Bombay in the field of Water Distribution Systems. In 1988, he joined Fluid Control Research Institute, where he is working in the areas of water distribution systems, flow products testing and calibration, quality systems, site measurements and filed efficiency testing of Hydroturbines. Presently, he heads the Center for Water Management in Fluid Control Research Institute.

Commodore (Retd) S. Saseendran is a Post Graduate in Electronics & Communication and also Master in Management Sciences (MMS). He was holding many responsible positions like Deputy Project Manager at IGCAR for adopting nuclear technology in naval ships, electrical in-charge of complete Eastern Naval Command, Information Technology Advisor to Chief of Naval Staff, Member of I.T policy group of Ministry of Defence, Head of I.T Faculty (College of Defence Management, Hyderabad), Director of Projects (Electronics & I.T Products) for Advanced Technology Vessel (ATV) project etc. Presently, he is the Director of Fluid Control Research Institute (FCRI), Palakkad.