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Research paper

Study on measurement uncertainty of energy conversion efficiency of tidal energy converters

Li Jian *, Song Yuze, Wang Huamei, Wang Xiangnan, Lu Kuan, Qiu Hongming

National Ocean Technology Center, Tianjin 300112, China

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ABSTRACT

Accurate assessment of the measurement uncertainty in the energy conversion efficiency of tidal energy converters is pivotal for a comprehensive analysis of experimental results. This paper presents a sophisticated measurement uncertainty assessment model which is based on energy conversion efficiency experiments of tidal energy converters. The model conducts a careful assessment of the input quantities using both Type A and Type B standard measurement uncertainties and provides an extended understanding of the experimental result uncertainties. The findings reveal that: (1) Even with human factors excluded, the experimental results show a dispersion ranging from 1.5 % to 4.2 % under the optimal experimental conditions; (2) Compared with the Type B standard measurement uncertainty evaluation method, the experimental results based on the Type A standard measurement uncertainty evaluation are more discrete, but the experimental results are more realistic; (3) Through the data analysis of the experimental results, the flow rate becomes a primary factor influencing the measurement uncertainty of experimental results. This paper provides a theoretical reference for scientific analysis of energy capture efficiency of tidal energy converters and for improving the credibility of experimental results.

1. Foreword

With the increasing development of global ocean energy technologies, the associated development risks have also risen (Chen et al., 2018; Guillou et al., 2020). How to effectively manage these risks and prevent the premature development of immature key technologies has become an urgent concern for global ocean energy development and utilization. Particularly noteworthy is the fact that ocean energy power generation devices are expected to operate in challenging marine environments, including exposure to strong storms and swell effects (Djebarri et al., 2020; Guillou et al., 2020). Robust laboratory testing stands out as crucial and effective means to mitigate these risks. Tidal current energy is widely used internationally for its large installed capacity of converters, high technological maturity and resource stability(Panda et al., 2018). For instance, the United Kingdom successfully connected the SeaGen tidal current energy device (1.2 MW) to the grid in 2008, generating 0.75GWh of electricity annually. Similarly, the first unit of the MeyGen project was connected to the grid in November 2016 and, as of December 2019, has generated 24.7 million kWh of electricity, which creates £7.1 million of revenue(Sun and Chen, 2024). In the same year, an ATIRT unit from Spain's Magallanes Renovables was connected to the grid at European Marine Energy Centre. Furthermore, in 2022, China's Hangzhou Lindong New Energy Science and Technology Co. Ltd successfully connected a tidal energy generator set to the grid on Xiushan Island in Hangzhou City, Zhejiang Province(Xia et al., 2022). Despite strict adherence to test standards and the use of high-precision measuring instruments, the researchers have identified a significant gap between the actual operation data of the tidal energy converters and laboratory test data. To address this gap, Amy Robertson et al. drew inspiration from studies on floating wind turbines, highlighting the existence of uncertainty between measurements and experimental results. Using Monte Carlo method, they quantified the uncertainty distribution of inputs and outputs (Robertson et al., 2020). Mahyar Ramezani further classified sources of uncertainty into physical, modeling, statistical, and measurement uncertainties(Ramezani et al., 2023). Xia Hai-Nan et al. analyzed the impact of measurement uncertainty on the assessment of power performance in tidal energy converters and calculated the sensitivity coefficients of inputs(Xia et al., 2023). Kreitmair and piano had extensively studied the uncertainty of measurement in the assessment of tidal energy resources and the prototype of tidal energy

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* Corresponding author.
E-mail address: lijian_1002@163.com (L. Jian).

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converter, and analyzed comparatively using a model simulation approach. (Kreitmair and Monika Johanna, 2019; Piano et al., 2017). Measurement uncertainty is a specific quantitative value of the dispersion of measurement results. The evaluation of measurement uncertainty of data results in the laboratory stage can accurately reflect the verification and simulation of laboratory test data, and provide effectively redundant and reliable data support for the instrumentation or device to enter the next stage of testing. Therefore, in order to deeply study the uncertainty of experimental results, improve the accuracy of laboratory test data and enhance the reproducibility of experimental data. Based on the analysis of the influence of flow velocity, blade diameter, power and other parameters for the measurement uncertainty of energy conversion efficiency, this paper constructs the evaluation model of measurement uncertainty of energy conversion efficiency of tidal energy converters, gives the detailed steps of measurement uncertainty evaluation, and uses Type A and Type B standard measurement uncertainty requirements to quantitatively analyze the test results, which provides effective experimental data support for the research and development of tidal energy converter.

2. Introduction to measurement uncertainty

Measurement uncertainty is a non-negative parameter that represents the dispersion of measured values(An et al., 2018). In the field of measurement, measurement results are incomplete only as measured estimates, and measurement uncertainty is also required to represent the reliability of measured values(China National Accreditation Service for Conformity Assessment, 2019, 2015). the concept of “uncertainty” originated in 1963. In 1993, ISO published Guide to the Expression of Uncertainty in Measurement (GUM)(BIPM et al., 2008), providing a method for assessing the measurement uncertainty based on the propagation law of measurement uncertainty. With the continuous development of measurement technology, measurement uncertainty has been recognized by more and more institutions and laboratories. GUM was recognized by International Laboratory Accreditation Cooperation (ILAC) in 2008, and GUM was used in measurement uncertainty of measurement results in subsequent detection or calibration activities (Coelho et al., 2021). GUM is applicable to both linear models and nonlinear models that can be expanded to linearity by Taylor series expansion. When using GUM, the measurement model should first be determined and the source of measurement uncertainty analyzed, then the component of standard uncertainty evaluated, and finally the synthetic standard uncertainty and extended uncertainty calculated.

The general process of GUM method for assessing measurement uncertainty is outlined in Fig. 1:

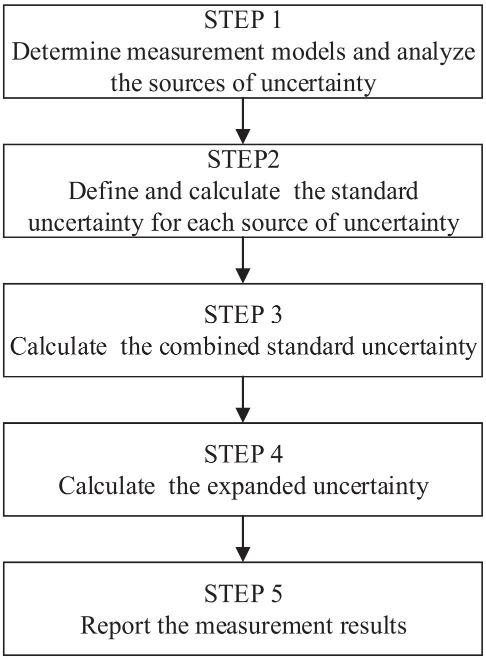

Fig. 1. General Process of Measurement Uncertainty Assessment using the GUM Method.

3. Establish measurement uncertainty assessment model

3.1. The measurement models and the sources of uncertainty

In conducting uncertainty assessment for the conversion efficiency of tidal energy converters, the first step involves establishing the calculation formula for conversion efficiency of the tidal energy converter. Subsequently, an analysis of the standard measurement uncertainty for each input variable is performed, as shown in Eqs. (1)-(3)(Wang et al., 2022):

$$\eta = \frac{P_2}{P_1} \times 100\% \tag{1}$$

Where:

P_1 - Incident flow power, measured in kilowatts (kW);
P_2 - Power generation, measured in kilowatts (kW).

$$P_1 = \frac{1}{2}\rho v^3 A \times 10^{-3} \tag{2}$$

Where:

ρ - Density of water, measured in kilograms per cubic meter (kg/m^3);
A - Area of the impeller, typically calculated using the formula for the area of a circle, measured in square meters (m^2);
v – Velocity, as a sample value, measured in meters per second (m/s).

$$A = \pi r^2 \tag{3}$$

Where:

r - Radius of the tidal energy converter model impeller, measured in meters (m).

In the above formulas, the energy conversion efficiency η of the tidal energy converter is composed of variables P_1 and P_2. P_2 is directly measured by the power analyzer, while P_1 is comprised of ρ, v, and A. A is calculated from r. Therefore, this paper presents the measurement uncertainty model and sources of uncertainty for the energy conversion efficiency of the tidal energy converter. Refer to Fig. 2 for details.

3.2. The standard uncertainty

The standard uncertainty of input variables is categorized into Type A and Type B standard uncertainties based on their sources (Sener et al., 2023). Under specified measurement conditions, the measurement uncertainty assessment conducted with statistical analysis is referred to as Type A standard measurement uncertainty assessment. As for Type A standard measurement uncertainty, it is required that n independent measurements be made at first to get the best estimated value, and then the result is achieved by calculating the experimental standard deviation. Type A standard measurement uncertainty assessment can be calculated according to the requirements of GUM 4.2 “Evaluation of Type A standard measurement uncertainty.” Assuming there are N input variables in the experiment, and each variable is measured for n sets of data. The average value of n sets of data $X_1, X_2, X_3\ldots X_\mathrm{n}$ is$\overline{X}$.The formula for the measurement uncertainty of the input quantity $u(x_i)(i\in n)$ is shown in formula (4):

$$u(x_i) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Xi-\overline{X})^2}\Big/\sqrt{n} \tag{4}$$

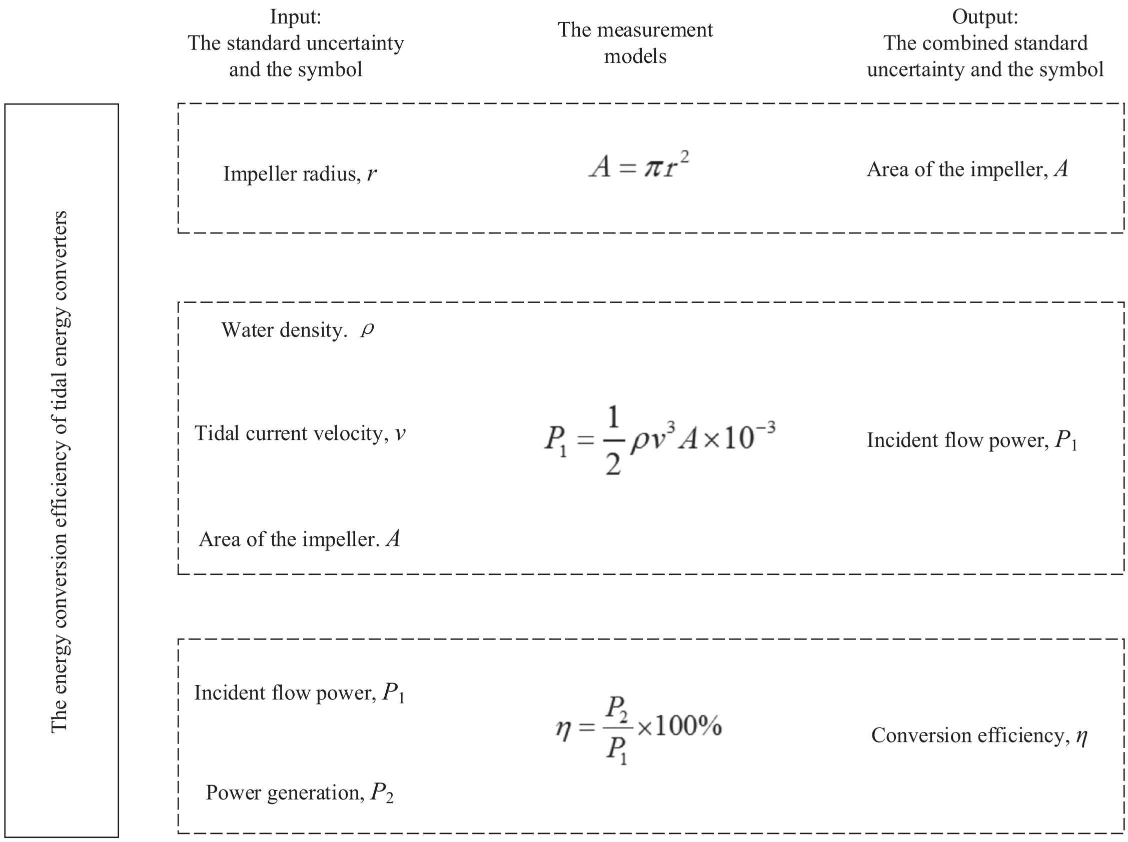

Fig. 2. Measurement Uncertainty Model and Sources for Energy Conversion Efficiency of Tidal Energy Converters.

Alternatively, Type B standard measurement uncertainty refers to the assessment of measurement uncertainty using calibration certificates, instrument accuracy grades, or values published by authoritative bodies. Before the evaluation of Type B standard measurement uncertainty, the possible interval value of the measurement shall be determined, and the corresponding coverage factor shall be determined according to the probability distribution of the measurement, and the more commonly used probability distribution models include normal, triangular, trapezoidal, rectangular (uniform) distribution, etc., whose corresponding coverage factor can be found in GUM 4.3 “Evaluation of Type B standard measurement uncertainty”. Meanwhile, GUM 4.3 also gives specific requirements for the evaluation of Type B standard measurement uncertainty.

3.3. *The combined standard uncertainty*

When the various input variables are independently uncorrelated, their combined standard uncertainty can be expressed as:

$$u_c^2(R)=\sum_{i=1}^{N}\left[\frac{\partial R}{\partial x_i}\right]^2 u^2(x_i) \tag{5}$$

Where:

R- Value of the output, function of input quantity x_i;

$u_c(R)$- combined standard uncertainty;

$u(x_i)$- standard measurement uncertainty of each input variable.

The $u(x_i)$can be rated in Type A or in Type B. The $\frac{\partial R}{\partial x_i}$ of the above equation is the partial derivative of the correlation function between the measured and the input variable with respect to the input quantity x_i, also known as the sensitivity coefficient.

3.4. *The expanded uncertainty*

The expanded uncertainty (U) is obtained by multiplying the coverage factor with the combined standard uncertainty, as shown in Eq. (6)

$$U=k\cdot u_c(R) \tag{6}$$

Where:

k - Coverage factor;

u_c (R) - combined standard uncertainty.

Under the conditions of a normal distribution, when the interval determined by the expanded uncertainty is required to be close to the level of confidence, the coverage factor (k) can be chosen to represent a specific relationship with the level of confidence (p). Generally, when selecting a 95 % confidence level for the expanded uncertainty, the corresponding value of k is about 2. The relationship between k and p is shown in Table 1.

3.5. *Report the measurement results*

In typical experimental measurements, the experimental result

Table 1
The correspondence between Coverage factor and Level of confidence for Normal distribution.

Level of confidence p (percent)	**Coverage factor** k
68.27	1
90	1.645
95	1.960
95.45	2
99	2.576
99.73	3

(output variable) is often a specific numerical value and a SI unit. To further describe the dispersion of the experimental result, the theory of measurement uncertainty assessment represents the experimental result by a measured value and an expanded measurement uncertainty, as shown in Eq. (7).

$$Y = y \pm U. \tag{7}$$

Where:

Y-output variable (i.e., experimental result);

y-measured value (i.e., measurement value, obtained value);

U-expanded uncertainty.

In the above formula, U represents the measurement uncertainty of this experiment. A smaller measurement uncertainty indicates a lower level of dispersion in the results of repeated experiments, reflecting higher accuracy in the experimental data

4. Validation of the measurement uncertainty assessment model

4.1. Experimental environment

The experimental validation of the measurement uncertainty assessment model for the energy conversion efficiency of tidal energy converters was conducted in the circulating water tank at the National Ocean Technology Center (NOTC) of China. The circulating water tank, designed and constructed by the NOTC, is 75 m long, 1.6 m wide, and designed with water depth of 1.2 m. Equipped with flow-generating pumps; the tank can generate circulating water flow with velocities ranging from 0.5 m/s to 2.6 m/s and waves up to 0.4 m in height. Eight groups of test conditions were mainly set in this test, and the flow rate ranged from 0.5 m/s to 1 m/s. See Fig. 3 for the test environment.

4.2. Experimental setup

The tidal energy converter used in this experiment was developed by the NOTC. The tidal energy converter consists of a generator, a speed increaser, a conductive slip ring, a transmission shaft and an impeller. The device is 1.8 m long and 1 m in diameter, with a designed maximum working speed of 1.5 m/s, a rated working speed of 1 m/s and a rated generating power of 60 W. Details of the device and experimental layout are illustrated in Fig. 4.

4.3. Calculation of standard measurement uncertainty

The load of the tidal energy converter in this experiment is a resistive wire. Experimental validations were conducted for 8 experimental conditions, and the average flow velocity, power generation, and energy conversion efficiency for each experimental condition are shown in Table 2.

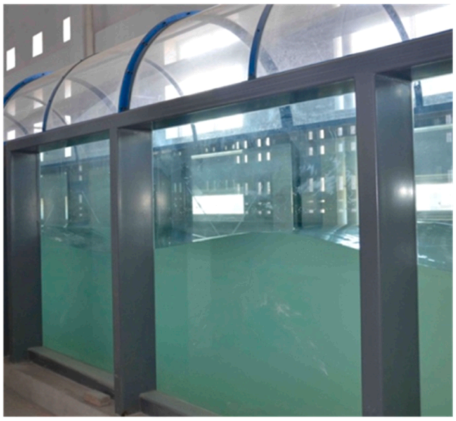

Fig. 3. The circulating water tank at the NOTC of China.

Fig. 4. Tidal Energy Converter and Experimental Procedure.

Table 2
Experimental conditions and experimental results of the tidal energy converter.

Experimental condition	Flow velocity (m/s)	Power generation (w)	Energy conversion efficiency (%)
1	0.531	9.578	20.10
2	0.583	12.453	19.79
3	0.627	14.211	17.88
4	0.719	19.570	16.56
5	0.781	28.204	18.70
6	0.849	37.585	19.26
7	0.920	47.544	19.21
8	1.002	50.913	16.02

In this paper, experimental condition 1 is taken as an example to validate the measurement uncertainty assessment model. The Type A standard measurement uncertainties and Type B standard measurement uncertainties for each input parameter are provided, calculated as follows:

(1) Power generation

In the experiment of tidal energy conversion efficiency under condition 1, a total of 50 sets of power generation data were analyzed. The average power generation was 9.578×10^{-3} kW. Calculated according to formula (4), the Type A standard measurement uncertainty $u(P_2)$ for power measurement was determined as 1.38×10^{-4} kW. The power collection in the tidal energy conversion efficiency experiment was performed using a power analyzer, which was calibrated and certified with China National Accreditation Service for Conformity Assessment (CNAS) qualification. The Type B standard measurement uncertainty $u(P_2)$ for power measurement obtained from the calibration certificate was 6.5×10^{-5} kW."

(2) Water density

The direct measurement of water density is challenging. In this paper, we adopted the research findings of Chinese scholars, such as Shi et al. (Shi and Zheng, 2015). The research indicates that, when g = 9.81 m/s^2, the relationship between temperature and density can be expressed by Eq. (8):

$$\rho = 1000.1 + 0.0552 \times t - 0.0077 \times t^2 + 0.00004 \times t^3 \tag{8}$$

Where: t - temperature of water, measured in℃.

In this experiment, the researchers used a thermometer to estimate water density by measuring temperature. The thermometer used in the experiment was a Class II mercury thermometer, and the obtained average water temperature was 17.1°C. Applying Eq. (8) with g=9.81 m/s^2, the calculated water density at this temperature was 999.01 kg/m^3. According to the uncertainty assessment theory, after 10 repeated measurements of water temperature, the Type A standard measurement uncertainty $u(\rho)$ for water temperature measurement was determined to be 0.03°C. Considering the accuracy grade of the thermometer with a minimum division value of 0.1°C and a resolution of 1/10th of the division value, the maximum allowable error is ±0.005°C. Since the scale of the thermometer is uniformly distributed, according to the assessment requirements of Type B standard measurement uncertainty, when a uniform distribution is assumed, the coverage factor was $\sqrt{3}$. Therefore, the Type B standard measurement uncertainty $u(\rho)$ for water temperature measurement was 0.003°C. Substituting the Type A and Type B standard uncertainties of water temperature measurement into Eqs. (5) and (8), the Type A standard measurement uncertainty for water density measurement was found to be 5×10^{-3} kg/m^3, and the Type B standard measurement uncertainty was 3.5×10^{-4} kg/m^3.

(3) Flow velocity

The flow velocity measurements in the experiments were made with vectrino from Nortek, Denmark. The working temperature of the measuring instrument is −4 ℃to 32 ℃, with a measurement accuracy of 0.5 % of the measured range or ±0.5 mm/s, The set flow rate measurement range is from 0 m/s to 1 m/s. For Condition 1, a total of 50 sets of flow velocity data were collected, with an average velocity of 0.531 m/s. By using Eq. (4), the Type A standard measurement uncertainty $u(v)$ for flow velocity measurement was calculated to be 3.9×10^{-3} m/s.

To conservatively calculate the Type B standard measurement uncertainty of flow velocity measurements, the measurement error of the flow velocity measurement equipment is selected as 0.5 % of the measured range (0 m/s to 1 m/s) . Consequently, the interval half-width is 2.5 mm/s, resulting in a Type B standard measurement uncertainty $u(v)$ of 1.4×10^{-3} m/s.

(4) Blade radius

The blade radius was measured using a SATA 10 m steel tape measure. After conducting repeated measurements of the blade radius 20 times, the average value was determined to be 0.450 m. Calculating according to Eq. (4), the Type A standard measurement uncertainty $u(r)$ for blade radius measurement was found to be 9.9×10^{-4}m. Simultaneously, based on the calibration certificate, the Type B standard measurement uncertainty u(r) was determined to be 3.5×10^{-5}m when the steel tape measure measured lengths in the range of 0–1 m.

4.4. Calculation of combined standard measurement uncertainty

As the actual power generation varies with changes in blade radius, flow velocity, and water density, there exists a correlation between the average incident flow power P_1 and the power generation P_2. To address the correlation between input quantities, a method proposed by Ni Yucai et al. was employed, which involves using different instruments to measure each input quantity. Since the indication errors between different instruments are uncorrelated, the measured results' dispersion is also uncorrelated (Ni and Yu, 2014). All input quantities in this experiment were measured using different instruments, ensuring that the measured values of each input quantity are uncorrelated. The calculation of the combined standard measurement uncertainty according to Eqs. (1)-(3) can be obtained as follows:

$$u_c^2(\eta) = P_1^{-4}P_2^2u^2(P_1) + P_1^{-2}u^2(P_2) \tag{9}$$

$$u^2(P_1) = \frac{v^6A^2}{4}u^2(\rho) \times 10^{-6} + \frac{9\rho^2v^4A^2}{4}u^2(v) \times 10^{-6} + \frac{\rho^2v^6}{4}u^2(A) \times 10^{-6} \tag{10}$$

$$u^2(A) = 4\pi^2r^2u^2(r) \tag{11}$$

The average values and standard measurement uncertainties of the measured power generation, water density, flow velocity, and radius for experimental condition 1 are presented in the table below:

The standard measurement uncertainty of each input quantity in accordance with the GUM can be determined using either Type A or Type B evaluation. To investigate the impact of Type A and Type B standard measurement uncertainty evaluations on the experimental results, this paper separately calculated the uncertainty components obtained from both methods for experimental condition 1 using formulas (9)-(11). The results are as follows:

For the synthesis of the uncertainty of the tidal energy converter's energy conversion efficiency (η) based on Type A standard measurement uncertainty evaluation:

$u_{cA}(\eta)$=5.38×100%

For the synthesis of the uncertainty of the tidal energy converter's energy conversion efficiency (η) based on Type B standard measurement uncertainty evaluation:

$u_{cB}(\eta)$=2.08×100%

4.5. Calculation of expanded uncertainty and representation of measurement results

Under normal distribution, with a confidence level of 95 %, the coverage factor k is about 2. Therefore, the expanded uncertainty is calculated as follows:

Base on Type A standard measurement uncertainty evaluation: $U_{cA}(\eta)$=10.8×100 %;

Base on Type B standard measurement uncertainty evaluation: $U_{cB}(\eta)$=4.2×100 %;

So, the measurement results of the tidal energy converter's energy conversion efficiency (η) for experimental condition 1 are expressed as follows:

Base on Type A standard measurement uncertainty evaluation: η_A=20.1 %±10.8 %;

Base on Type B standard measurement uncertainty evaluation: η_B=20.1 %±4.2 %.

4.6. Analyses

To provide a more comprehensive representation of the measurement uncertainty of the experimental results, this paper conducted uncertainty assessment analyses for the experimental outcomes under conditions 2–8. The obtained results are as follows:

The factors influencing the measurement of experimental results are numerous, typically including environmental factors, instrument-related factors, and inherent factors of input quantities (Judge et al., 2021). For instance, considering the measurement uncertainty analysis of the energy capture efficiency of the tidal energy converter, it is evident that different experimental conditions correspond to varying expanded uncertainties. Even under the assumption of eliminating human factors in the same experimental condition, using Type B standard measurement uncertainty assessment, the experimental results still exhibit a dispersion within the range of 1.5–4.2 %, owing to the inherent differences in the measurement accuracy of the measuring devices. Furthermore, as observed in Figs. 5–7, the expanded uncertainty based on Type A standard measurement uncertainty assessment is significantly larger than that based on Type B, but the two exhibit similar trends. Additionally, through the analysis of Eqs. (9) - (11) and Table 3 in this test, it can be seen that compared with water density, area of the impeller, The calculation results of the standard measurement uncertainty and the corresponding sensitivity coefficient for the flow velocity measurement $\left[\frac{9\rho^2v^4A^2}{4}u^2(v)\right]$ have the largest order of magnitude, so the flow velocity is the most significant impact for the measurement uncertainty assessment model of the test results. Lastly, from the analysis,

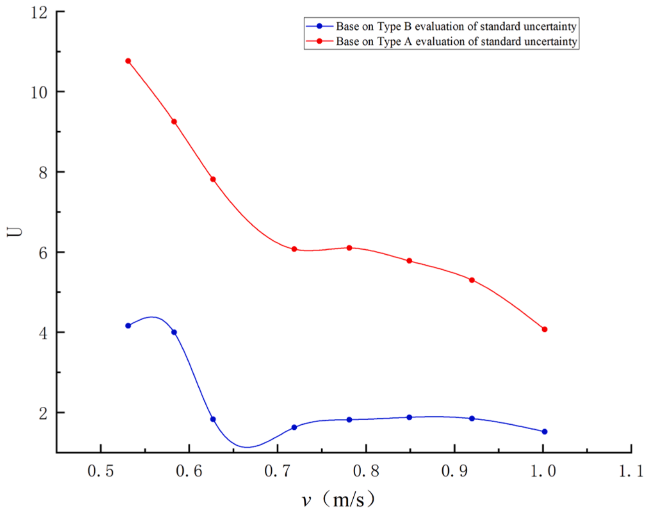

Fig. 5. Curve diagrams based on Type A standard measurement uncertainty evaluation and Type B standard measurement uncertainty evaluation.

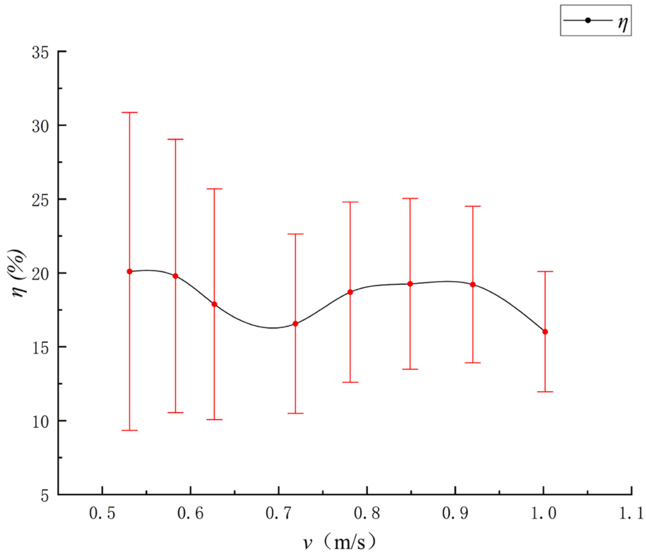

Fig. 6. Efficiency diagram based on Type A standard measurement uncertainty assessment.

it is apparent that in low-flow conditions, the difference in expanded uncertainty between Type A and Type B standard measurement uncertainty assessments is substantial. Since the minimum flow rate of the flow generating equipment is 0.5 m/s, this discrepancy may be attributed to the instability of low-speed flows generated by the flow-generating equipment. As the flow velocity increases, the measurement uncertainty of the experimental results tends to converge.

4.7. Validation

In general, the adoption of formula 5 has been fully applicable to the measurement uncertainty assessment of most parameters, but since formulas 1 and 2 are not non-linear, it is necessary to validate whether GUM method is applicable to the study in this paper, so as to improve the rigor of the research results. When the measurement function is nonlinear, the method of 4.4 in JJF 1059.1–2012 is used in this paper (AQSIQ/MTC1, 2013), and the synthetic uncertainty of the input quantities is calculated in formula 12.

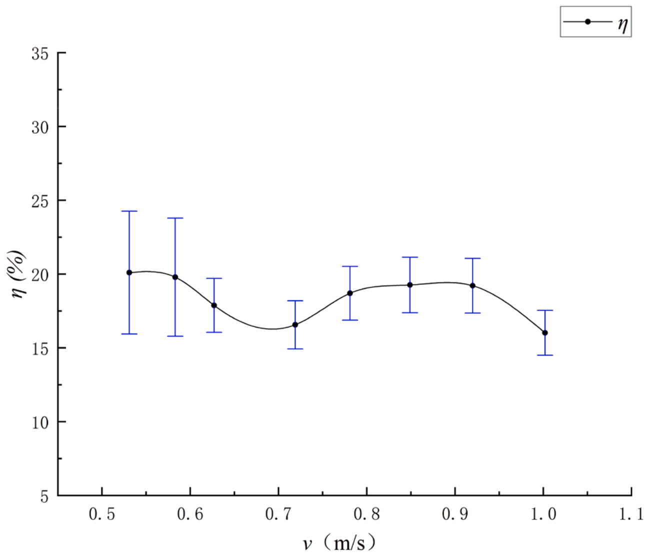

Fig. 7. Efficiency diagram based on Type B standard measurement uncertainty assessment.

Table 3
The average values and standard measurement uncertainties of the measured power generation, water density, flow velocity, and radius under experimental condition 1.

Experimental condition 1	Power generation P_2 (kW)	Water density ρ (kg/m^3)	Flow velocity v (m/s)	Blade radius r (m)
average value	9.578×10^{-3}	999.01	0.531	0.450
Type A standard measurement uncertainty	1.4×10^{-4}	5.0×10^{-3}	3.9×10^{-3}	9.9×10^{-4}
Type B standard measurement uncertainty	6.5×10^{-5}	3.5×10^{-4}	1.4×10^{-3}	3.5×10^{-5}

$$u_c^2(R)=\sum_{i=1}^{N}\left[\frac{\partial R}{\partial x_i}\right]^2 u^2(x_i)+\sum_{i=1}^{N}\sum_{j=1}^{N}\left[\frac{1}{2}\times\left(\frac{\partial^2 R}{\partial x_i\partial x_j}\right)+\frac{\partial R}{\partial x_i}\times\frac{\partial^3 R}{\partial x_i\partial x_j^2}\right]u^2(x_i)u^2(x_j) \tag{12}$$

As can be seen from Table 3, whether it is Type A standard measurement uncertainty evaluation or Type B standard measurement uncertainty evaluation, the magnitude of $u^2(x_i)u^2(x_j)$result in formula 12 is much smaller than$u^2(x_i)$, which is almost negligible in mathematical calculation. Therefore, it is appropriate to adopt formula 5 to carry out measurement uncertainty assessment of energy conversion efficiency of tidal energy converters in this paper.

5. Conclusions

Measurement uncertainty assessment is a procedural method to characterize the “accuracy” and “how accurate” of measurement results through theoretical foundations, data calculations, etc. In this study, a measurement uncertainty assessment model for the energy capture efficiency of tidal energy converters was established based on the theory of measurement uncertainty assessment. The GUM method was employed to quantify the measurement uncertainty, and the effects of Type A and Type B standard measurement uncertainties on the measurement results were analyzed separately. The following conclusions were drawn:

Table 4
The experimental results and expanded uncertainties for experimental conditions 2–8.

Experimental condition	Flow velocity (m/s)	Power generation (kW)	Energy conversion efficiency (%)	Expended uncertainty	
				Base on Type B evaluation of standard uncertainty	Base on Type A evaluation of standard uncertainty
1	0.531	0.00958	20.1	4.2	10.8
2	0.583	0.01245	19.8	4.0	9.2
3	0.627	0.01421	17.9	1.8	7.8
4	0.719	0.01957	16.6	1.6	6.1
5	0.781	0.02820	18.7	1.8	6.1
6	0.849	0.03759	19.3	1.9	5.8
7	0.920	0.04754	19.2	1.9	5.3
8	1.002	0.05091	16.0	1.5	4.1

(1) This article innovatively applies the theory of measurement uncertainty assessment to energy conversion efficiency of the tidal energy converters by laboratory testing, and quantifying the degree of dispersion of experimental results. Due to the measurement uncertainty is consistently present in the experimental results of the energy capture efficiency measurement of tidal energy converters. Even under optimal experimental conditions, the experimental results will still exhibit some degree of dispersion due to differences in the precision of measurement instruments. Therefore, the measurement uncertainty of the results should be considered when applying experimental results in engineering applications.

(2) Compared with the results obtained from the Type B standard measurement uncertainty assessment, the results obtained from Type A standard measurement uncertainty assessment based on statistical principles show a greater degree of dispersion. Because Type A standard measurement uncertainty assessment is influenced by human factors, experimental environment, and experimental facilities, The type B standard measurement uncertainty assessment relies more on calibration certificates, instrument accuracy grades, or values published by authoritative bodies. Therefore, to a certain extent, the experimental results based on Type A standard measurement uncertainty assessment are more suitable for practical application.

(3) In measurement uncertainty assessment, the sensitivity coefficient of flow velocity measurement has the greatest impact on the extended measurement uncertainty, and the measurement uncertainty becomes progressively smaller as the flow velocity increases. This may be attributed to the instability of the flow generation equipment. Therefore, in order to improve the precision of experimental results under laboratory conditions, efforts should be made to minimize the impact of flow velocity fluctuations on the experimental results.

In summary, the degree of dispersion in experimental results can be quantitatively characterized using measurement uncertainty assessment theory. This study provides a theoretical reference for scientific analysis of the energy capture efficiency of tidal energy converters and for improving the credibility of experimental results. In addition, this study can provide an effective redundant design support for the manufacturing of engineering prototypes of tidal energy converters based on laboratory test data.

CRediT authorship contribution statement

Li Jian: Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Wang Huamei:** Data curation. **Song Yuze:** Formal analysis. **Wang Xiangnan:** Conceptualization. **Qiu Hongming:** Project administration. **Lu Kuan:** Methodology.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Li Jian reports financial support was provided by Ministry of Natural Resources of the People's Republic of China. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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