A new assembled experimental device for fluid mechanics

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Abstract. Fluid mechanics is one of the important branches of basic mechanics education of science and technology in higher education, and its corresponding teaching experiments are numerous. However, there are great similarities among some components of most traditional hydrodynamics experimental devices. If an independent experimental device is designed for a specific experiment, it will result in a great waste of resources and space. Therefore, based on the full investigation on the similar components of some certain experimental devices, this study redesigned and integrated them, and innovatively proposed a new type of assembled hydrodynamics comprehensive experimental device. This experimental device can be utilized to carry out Reynolds experiment, Nozzle outflow experiment, Karman vortex street experiment, etc. based on different combinations. The corresponding results show that this assembled hydrodynamics comprehensive experimental device has the advantages of multiple functions, small occupied space, low cost, good stability, high corrosion resistance, strong expandability, and so on.

Keywords: Fluid mechanics, Comprehensive experimental device, Assembly type, Expandable.

1. Introduction

Fluid mechanics is one of the important branches of basic mechanical education in science and engineering disciplines at higher education institutions, and related teaching experiments play a crucial role in the instruction of fluid mechanics, representing a key component of the mechanics curriculum. Classical experiments in fluid mechanics education include the incompressible fluid steady flow energy experiment (i.e., Bernoulli experiment), Venturi experiment, Reynolds experiment, and Karman vortex street experiment. To reduce costs associated with the purchase, assembly, maintenance, and storage of such experimental devices, researchers have developed a series of comprehensive fluid experimental devices, such as those assembled from discarded materials into a space-saving foldable fluid mechanics demonstration experimental device [1], and a multifunctional fluid mechanics experimental platform created by parallel connection around a water storage tank [2]. There are also some more mature large-scale comprehensive experimental devices. Researchers have improved existing Reynolds experimental setups by conducting lateral multi-tube parallel connections or

diversified layered modifications of pipelines to meet comprehensive experimental needs [3-5]. Some researchers have also used vertical height differences in water tanks, adjusting water head energy and comparing flow stabilization effects to perform layered experiments in water tanks to achieve comprehensive experimental purposes [6].

From the perspective of development history and usage, current comprehensive fluid mechanics experimental devices are relatively mature. However, deficiencies remain in aspects such as space usage, parts integration, utilization rate, lifespan, and precision, such as: fluid mechanics experimental devices capable of visualizing flow fields, where the density and dissolution speed of tracing agents like red ink or potassium permanganate solution significantly affect experimental precision, and the device interfaces have discontinuities in tube diameter (e.g., necked flat welding flanges) [7-9]. Additionally, some comprehensive experimental devices with viewing windows use corrosion-resistant stainless steel materials as the main components of the experiment, which makes the overall device expensive and unsuitable for mass purchase by universities [10]. These deficiencies are the main reasons limiting the widespread application of high-performance, low-cost fluid mechanics experimental devices. Therefore, this study proposes a new type of modular fluid mechanics comprehensive experimental device, which boasts comprehensive experimental functions, good flow stabilization effects, strong expandability, low cost, and a long service life. The development of this device can greatly promote universities to establish well-equipped, fully functional basic fluid mechanics laboratories, thus improving the related disciplinary training system [11-14].
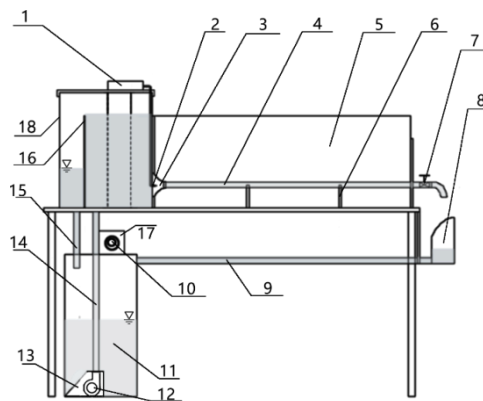
2. Experimental Device

The modular fluid mechanics comprehensive experimental device can be used to perform Reynolds experiments, Karman vortex street experiments, and nozzle outflow experiments. The device overall is divided into common components and specific components. Common components mainly include the flow stabilization water tank, water storage tank, and fluid circulation components; specific components mainly include the Reynolds outflow component, Karman vortex street open channel component, and nozzle and orifice outflow component.

2.1. Common Components

#### 2.1.1. Water Storage Tank and Fluid Circulation Components

As shown in Figure 1, the water storage tank used in this modular fluid mechanics comprehensive experimental setup measures 700mm×500mm×1000mm. To ensure effective fluid circulation during experiments, the water storage should be at least 80% of the tank's volume. Based on ergonomic needs, the operating height is approximately 1.3m; hence, a water pump with a maximum lift of 2m is selected. The water pump, inlet pipe, return water filtration trough, and return water pipeline together constitute the fluid circulation components.

Figure 1. Assembled hydrodynamics comprehensive experimental device.

2.1.2. Stabilization Water Tank

The stabilization water tank, part of the common components, is constructed from PMMA transparent plates and measures 500mm×410mm×250mm. It features an innovatively designed silica gel particle stabilization drawer, creating a removable core structure that is straightforward to disassemble, clean, and maintain. The drawer is filled with silica gel particles of varying diameters (S⌀4, S⌀6, S⌀8) and sealed with multiple plates and baffles. The drawer's design includes a perforated bottom for quick drainage and a specially designed overflow dam to prevent liquid splashing. The drawer and tank are equipped with V-shaped protrusions and grooves, facilitating easy assembly and providing enhanced sealing and stability, while also preventing damage during maintenance.

(a) Top view of steady flow tank.   (b) Steady current drawer
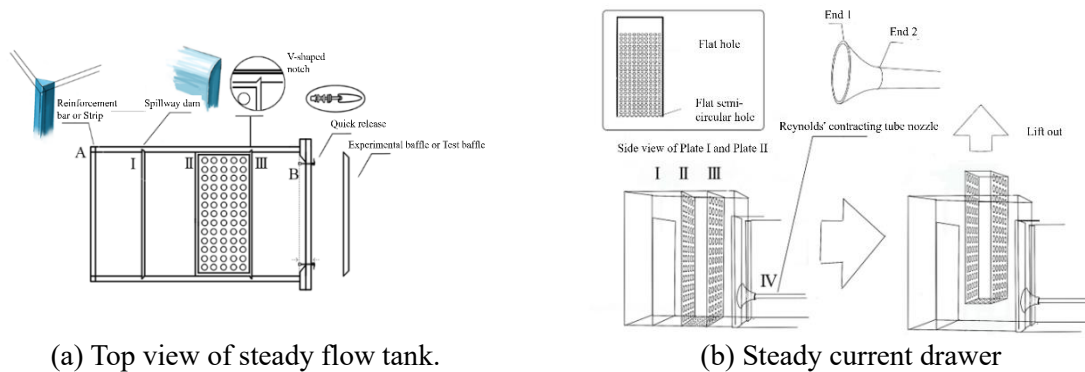
Figure 2. Water tank for regulating flow.

2.2. Specific Components

The modular fluid mechanics experimental device offers excellent expandability through interchangeable components tailored for various experiments such as Reynolds outflow, Karman vortex street, and nozzle or orifice outflow. It incorporates standardized removable interfaces and self-locking systems to allow quick and efficient component swaps, enhancing the device's versatility for different experimental setups.

2.2.1. Removable Interface and Corresponding Self-locking System

The newly designed standardized removable interface significantly reduces interface wear from frequent assembly and disassembly, enhancing the feasibility for adding experimental variations. The innovative quick-install self-locking sealing system replaces traditional glued methods, providing initial sealant protection against seepage and strengthening the seal as internal water pressure increases. This system allows for quick changes between experimental setups by simply releasing and swapping baffles and their specific components, streamlining the process for experiment personnel.

2.2.2. Reynolds Outflow Component

The Reynolds outflow component, which includes a removable baffle compatible with the device's standardized interface, a tracer dye guide aligned with fluid outflow direction, and an outflow pipe made of PMMA hollow tube material sized ⌀20×4. This setup also features an infinite flow valve at the pipe's rear to adjust fluid flow speed. The component contains a Reynolds tapered nozzle designed with a complex, derivable curve for diameter changes from ⌀100×6 to ⌀26×6, and is supported by an anti-roll frame to stabilize the outflow pipe.

2.2.3. Karman Vortex Street Open Channel Component

The Karman vortex street open channel component, which features an open section at location A and an overflow dam at location B to manage water levels and prevent splashing. The side baffles are constructed from PMMA transparent plates, measuring 1110mm×400mm×10mm, allowing clear observation of the Karman vortex street phenomenon. Both the overflow dam at location B and the

one in the stabilization water tank share an arc-shaped design, with dimensions of 150mm×300mm×10mm, enhancing fluid control and minimizing splashing.
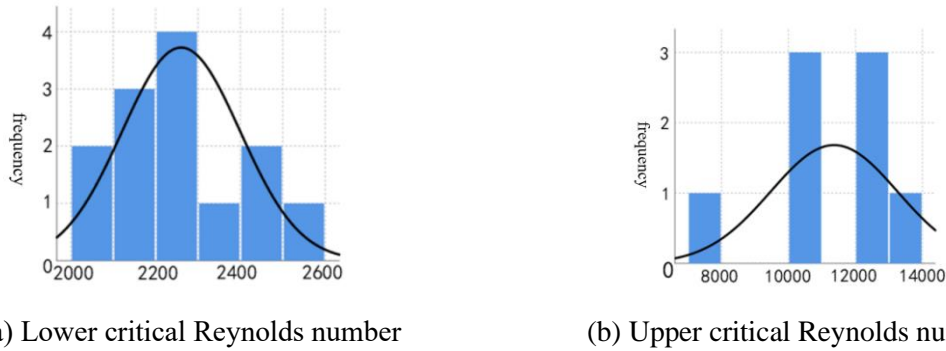
2.2.4. Nozzle and Orifice Outflow Component

The different nozzles and orifices used in this experiment are adjusted using a switching wheel, which is bolted to the stabilization water tank baffle. The nozzle interface diameter is ∅20mm, and nozzles of different shapes can be custom-made according to experimental needs and fixed at positions A, B, C with UV glue.

3. Experimental Methods and Results

3.1. Reynolds Experiment

The Reynolds number, a dimensionless value, gauges the influence of fluid viscosity by reflecting the ratio between inertial and viscous forces. It helps identify flow state transitions through critical Reynolds numbers, split into upper and lower thresholds. The upper threshold indicates the shift from laminar to turbulent flow and varies between 5,000 and 40,000, noted for its instability. In contrast, the lower critical Reynolds number, more stable at a value of 2,320, indicates the transition from turbulent back to laminar flow and is widely used in practical settings to determine the flow state [8, 16-18]. In the Reynolds outflow experiments conducted with the designed setup, critical Reynolds numbers were systematically analyzed. As shown in Figure 3, the findings include a single-sample K-S normal test confirming the normal distribution of the lower critical Reynolds numbers with a mean of 2260.7 and a standard deviation of 139.3. The upper critical numbers also normally distribute around a mean of 11362.4 with a standard deviation of 1897. These results align with established research on Reynolds numbers, underscoring the experimental setup's accuracy and practical utility for studying flow dynamics.

(a) Lower critical Reynolds number   (b) Upper critical Reynolds number

Figure 3. Single sample K-S normal test for upper and lower critical Reynolds number single.

3.2. Nozzle and Orifice Outflow Experiment

The experimental device uses a water head type instantaneous digital flowmeter, monitoring the flow through different nozzles and orifices in real-time. The flow rate q_V under the influence of water head H_0 for thin-walled nozzles or orifices in free outflow can be calculated using the following equation:

$$q_V = \varphi \varepsilon A \sqrt{2gH_0} = \nu A \sqrt{2gH_0} \qquad (1)$$

where $\varphi = 1/(1+\zeta)^{1/2}$ is the velocity factor, ζ is the resistance factor; $\varepsilon = A_c/A$ is the contraction factor, A_c and A are the contracted and cross-sectional areas, respectively; $\nu = \varepsilon\varphi$ is the flow factor; g is the acceleration due to gravity; $H_0 = H + \alpha v_0^2/(2g)$, since the water head $\alpha v_0^2/(2g)$ due to the velocity of nozzle and orifice outflow is minor, this term can be neglected.

The experiments depicted in Figure 6, showcasing various outflow projects from left to right—namely orifice, right-angle nozzle A, conical nozzle, and right-angle nozzle B—reveal significant variations in fluid flow rates despite minor differences in water levels. As summarized in Table 2,

these variations suggest that the nozzle and orifice shapes, alongside changes in the contraction area, substantially influence fluid outflow velocity. Further comparative analysis confirms that the experimental data aligns well within acceptable error margins with empirical values from Professor Mao Genhai's "Engineering Fluid Mechanics Experiment Guidebook" [16,17]. This alignment attests to the high accuracy and practical utility of this device for conducting detailed studies on nozzle and orifice outflow dynamics.

Table 2. Data of nozzle and orifice outflow experiment

Item	orifice	Right Angle nozzle A	Conical nozzle	Right Angle nozzle B
Flow q_v(10^{-6}m^3/s)	432.93	396.83	91.00	110.99
Working head H_0(10^{-2}m)	7.18	7.95	7.95	13.65
Outflow area A(10^{-4}m^2)	5.31	3.80	3.80	0.79
Flow factor v	0.69	0.84	0.191	0.87
Shrink section A_c(10^{-4}m^2)	3.80	3.80	0.79	0.79
Shrinkage factor ε	0.72	1	0.21	1
Flow factor φ	0.96	0.84	0.93	0.87
Drag factor ζ	0.08	0.42	0.16	0.33

3.3. Karman Vortex Street Experiment

This modular fluid mechanics experimental device offers an outstanding platform for observing the Karman vortex street phenomenon. Experiment personnel can finely adjust the tracer agent's flow rate with a high-precision syringe pump (SPLab02) to meet specific experimental needs. When the flow rate is set correctly, the Karman vortex street phenomenon manifests. Observers can then directly view or capture this phenomenon through the device's transparent PMMA baffle, as shown in Figure 4, providing a clear and direct visualization of the fluid dynamics involved.
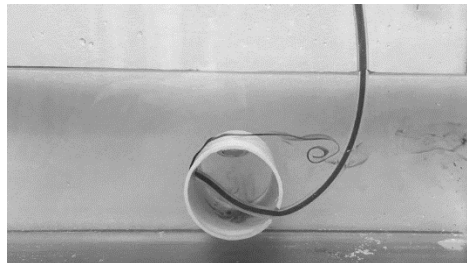
Figure 4. Picture of Karman vortex street.

4. Conclusion

In summary, this new modular fluid mechanics experimental device offers several advantages over traditional and similar devices: (1) It uses innovative removable stabilization components that improve both maintainability and stability; (2) Its design includes standardized removable interfaces that enhance expandability and reduce wear from frequent disassembly and reassembly; (3) The operation and observation platform, made from transparent PMMA, provides excellent sealing, ease of operation, and cost-effectiveness. Additionally, destructive testing has shown that the inclusion of reinforced bars significantly enhances the device's heat and corrosion resistance. During the educational phase, this device affords students substantial freedom to expand experiments, fostering engagement and cultivating their innovation and independence. Overall, this device is instrumental in developing well-equipped, fully functional basic fluid mechanics labs in universities, enhancing the educational framework within the discipline.

Acknowledgement

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