Project and Experiment-Based Fluid Dynamics Education

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Abstract—This paper presents the project and experiment-based fluid dynamics education in Meisei University, a private institution in Tokyo, Japan. We pay attention not only to the basic engineering courses but also to the practical aspect of engineering experience. So, we prepare courses called the Projects from I to VI. The Projects I and II are designed for the first year, III and IV are designated for the second year, V and VI are prepared for the third year, respectively. Each supervisor is responsible for two of these projects every year. When students take the Project V and VI at the third year, we automatically assume that these students will join the lab of the project for the graduation thesis. We would like to show our experience in the Project I in the summer term, 2016. In this project, we introduce a traction flight vehicle called Cat Flyer. This is a kind of a kite towed by a car for example. This is very similar to parasailing, but flight is possible even on the roads. Experiments in mechanical engineering education are also very important, and we would like to explain our course on centrifugal pump, venture, and orifice. Although these are described in detail in the text books of fluid dynamics, it is still crucial to have practical experiments as a student.

Keywords—Aerodynamics, experiment, fluid dynamics, project

I. INTRODUCTION

THIS paper describes the experimental and project-based fluid dynamics education in Meisei university. Fluid dynamics is sometimes a very difficult subject for many engineering students especially when the mathematical formulations are heavily involved. In Meisei university, we pay attention to the hands-on experience during the academic courses. It is interesting to note that major breakthrough is often brought by very practical people who are not necessarily academically excelled. One story is that bachelors contribute much more than people with doctor degrees in a huge manufacturing company in Japan. This is because that the practical experience in the real world is more useful as far as manufacturing is concerned. We are not saying that graduate education is not fruitful, but it depends on the situation. From this point of view, we weigh the project-based learning and the experiments in our courses.

II. TRACTION FLIGHT VEHICLE IN MEISEI PROJECT I

A. Project I in the First Term 2016

We have about 400 new undergraduate students in engineering and science, 2016. There are altogether 34 subjects for these newcomers: 5 for physics, 6 for life sciences and biochemistry, 6 for mechanical engineering, 8 for electronics and electrical engineering, 5 for architecture, and 4 for ecology. There are 15 weeks to complete the project. First week was an orientation for all students. Each department also gives instructions for their own students.

B. Project I in Mechanical Engineering

We provide: Traction Flight Vehicle, Material Strength, Air Engine, Mini Model Car, Pet Bottle Rocket, and Shape Memory Alloy. One subject accepts about ten students and weekly seminars follow. We have altogether fifteen weeks to complete the project.

C. Traction Flight Vehicle in Project I

The traction flight vehicle is similar to parasailing [1]. Although there exists already flying taxis and bikes, they are very difficult to develop and might be dangerous in daily life circumstances. So, we propose a traction flight vehicle where the driver and/or the pilot might be on the flying part [2]. We allow the traction flight vehicle connected to the driving vehicle primarily with pitching motion as in Fig. 1 where U is driving velocity and ω is the angular velocity of pitching motion. We can achieve a stable traction flight by restricting the degrees of freedom of the towed wing.
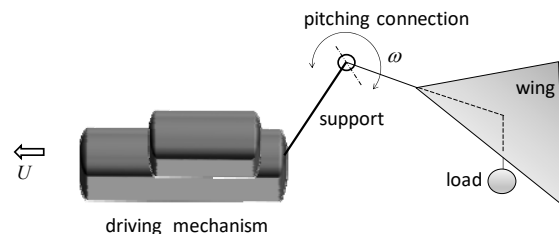

Fig. 1 Traction flight vehicle

After the first orientation, we explained the traction flight vehicle project. We made paper gliders [3] and model ground-effect vehicles [4] to get hands-on experience.

In the project, the lectures were given on the aerospace engineering and the aerodynamics which is not necessarily familiar in the mechanical engineering department. In many cases, airfoil theory and gas dynamics are missing in the mechanical syllabus. Then laboratory tour was conducted. We introduced several low-speed wind tunnels, water channel, and pump, venturi, orifice and weir. So, the students got the idea what about fluid dynamics and aerodynamics.

After the introductory process, the model parts of the traction flight vehicle were prepared.

Project I is also a course for the university open campus to the future engineers and scientists. Elementary school pupils

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and the junior high school students were invited to show how to build and operate the traction flight vehicle. During the course of development, the author and the students both realized that the aerodynamic concept of the traction flight vehicle had to be explained to the participants. The students studied the ground effect by conducting a wind tunnel test for that purpose.

The students prepared the model traction flight vehicle and practiced how to work them. In the open campus, we had one session in the morning and two extra sessions in the afternoon. Each session accepted about ten students and altogether more than thirty pupils joined the project. We introduced the model traction flight vehicle, and operated the traction flight vehicle.

After the practice, the participants reviewed the project. They experienced the application of aerodynamics by the traction flight vehicle. One of the critical comments by the accompanying parents was that we should include the assembling process of the traction flight vehicle to understand the structural aspect of the model.

III. Fluid Dynamics Experiment

We provide a course called mechanical engineering experiment I for the summer term from April to July. Third year students are divided into four groups, so we have about ten students in each group. Instructors prepare also four experimental items, i.e., gel material deformation, machining, pumps, and heat transfer. The author is responsible for the pump experiment. Each categorized experiment continues for successive three weeks. For the first two weeks, students work on the experiment. The final third week, they complete the experimental report with tables, graphs, and some discussions. We introduce our fluid dynamics experiment, i.e., the pump experiment, in the following section.

A. Pump and Weir

Students first set the 2.2 kW two-pole pump discharge pressure by regulating a valve and flow rate is determined. Mass flow rate is measured directly by a classical balance. Students measure the time to fill the tank for a given mass. This becomes the reference mass and the volumetric flow rate Q.

We also measure the water surface level of a regular triangular weir of 320 mm side length, Fig. 2, and obtain the volumetric flow rate Q form the hydrodynamic formula of JIS (Japan Industrial Standard). There are small discrepancies between the balance and the weir formula as shown in Fig. 3, where H is the weir head, K is a constant by JIS formula, and symbols denote students' group. But the agreement between the two methods is satisfactory from the practical point of view.

The pump suction pressure is measured and we can calculate the theoretical pump power. The pump motor input power is also measured, and we obtained the motor output power and its efficiency from a manufacturer's data chart. So, we finally get the efficiency of the pump η. Students draw the pump H(head) - Q curve, and the corresponding non-dimensional $\psi - \phi$ curve including the efficiency η as shown in Fig. 4, where $\phi \left(\equiv Q / nD^3 \right)$ is the flow coefficient and $\psi \left(\equiv gH / n^2 D^2 \right)$ is the head coefficient (D: diameter, g: gravitational acceleration,

n: revolution per second). We also calculate the specific speed $n_s \left(\equiv \phi^{1/2} / \psi^{3/4} \right)$.

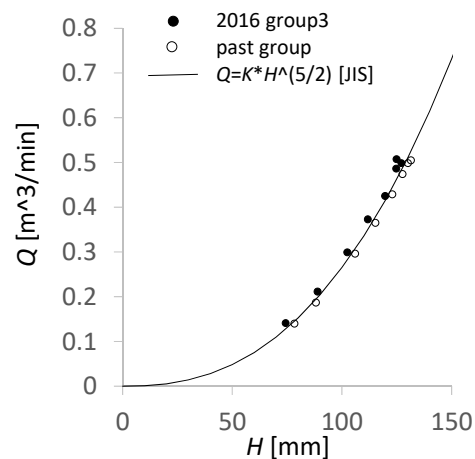Fig. 2 Regular triangular weir of 320 mm side length
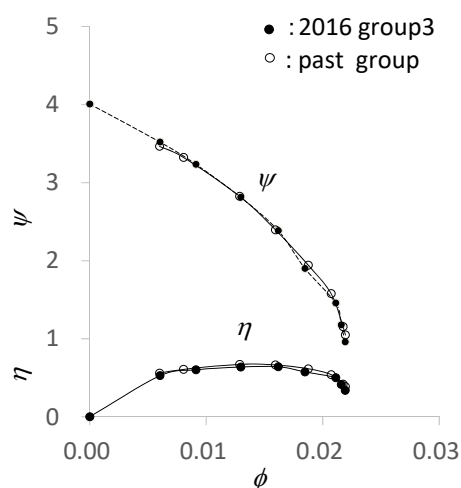

Fig. 3 Flow rate Q from triangular weir head H

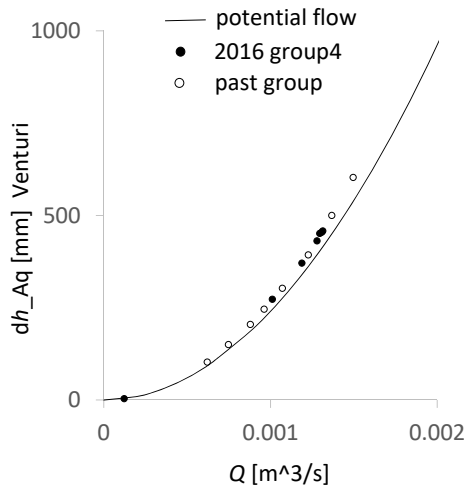Fig. 4 Pump head coefficient ψ and efficiency η

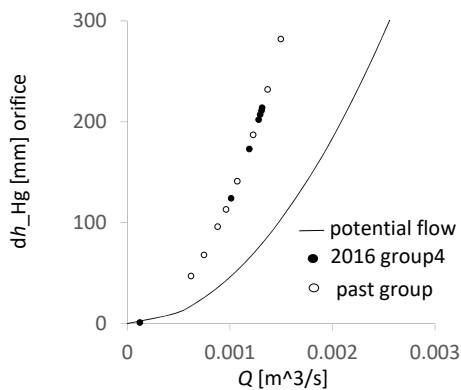Fig. 5 Venturi pressure drop $\dfrac{d_2}{d_1} = \dfrac{23}{35} \approx 0.66$ $[d] = $ mm

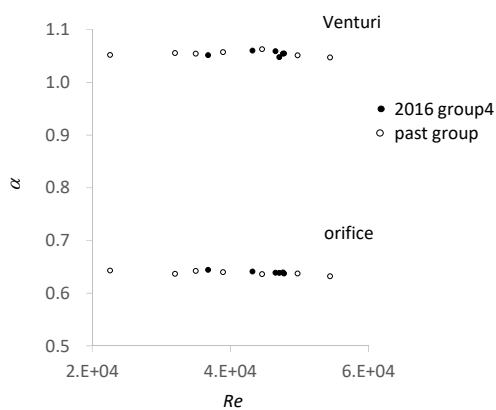Fig. 6 Orifice pressure drop $\dfrac{d_2}{d_1} = \dfrac{19}{35} \approx 0.54$ $[d] = $ mm

Fig. 7 Flow coefficient α

B. Venturi Tube and Orifice

One of the most famous fluid dynamic devices is a venturi. Students measure the pressure drop $\Delta h [\text{mm}] (\Delta p [Pa])$ by a U-tube water manometer and realize that a flow through the venturi is nearly a potential flow with small viscous effect. The flow rate from the venturi pressure drop Δh is several percentage smaller than that by the Bernoulli's prediction as shown in Fig. 5. The inlet pipe inner diameter is $d_1(=35$ mm$)$ and the throat diameter is $d_2(=23$ mm$)$.

An orifice is set in series behind the venturi and students experience higher pressure drop via the orifice than that of the venturi as shown in Fig. 6. Pressure drop is measured with a mercury-water U-tube manometer. The contraction is also higher for the orifice, with a throat diameter $d_2=19$ mm and a pipe diameter $d_1=35$ mm. Students have to pay attention not only to the density of mercury but also to that of water to calculate the pressure difference.

By changing the flow rate, we get the flow coefficient α of the ventrui and the orifice against the Reynolds number. The flow coefficient α is defined as the throat velocity divided by $\sqrt{2\Delta p / \rho}$, where ρ is the water density. These coefficients are nearly constant for the Reynolds number range tested as shown in Fig. 7.

IV. VISUALIZED POTENTIAL FLOW FOR STUDENTS

While our students conduct the fluid mechanics experiments, it might be very helpful if we can show the flow in the devices.

Although a complete viscous solution is possible these days, it is still very useful to show a simple potential flow image for basic understandings.

As for a two-dimensional nozzle which represents the venturi, we come to an idea that Laplace's equation may have analytical solution for the nozzle flow. Laplace's equation becomes

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = 0 \qquad (1)$$

where x, y is the coordinates, and ψ is the stream function. We assume the following form:

$$\psi = f(x)g(y) \qquad (2)$$

The solution becomes as:

$$\frac{f''(x)}{f(x)} = -\frac{g''(y)}{g(y)} = c$$

$$f(x) = A \cosh \sqrt{c}\,x + B \sinh \sqrt{c}\,x \qquad (3)$$

$$g(y) = C \cos \sqrt{c}\,y + D \sin \sqrt{c}\,y \qquad (4)$$

where A, B, C, c and D are all constants. We may put

$$\psi(x, y) = e^{-x} \sin y \qquad (5)$$

$$u = \frac{\partial \psi}{\partial y} = e^{-x} \cos y \tag{6}$$

$$v = -\frac{\partial \psi}{\partial x} = e^{-x} \sin y \tag{7}$$

$$p \equiv -u^2 - v^2 = -e^{-2x} \tag{8}$$

where p is the static pressure, u and v are the velocity components in the x- and y-directions, respectively. Figs. 8 and 9 show ψ and p, respectively. We can regard the constant stream function as a nozzle and/or a diffuser wall of the venturi. It must be emphasized to the students that the flow goes through the adverse pressure gradient as shown in Fig. 9. This situation causes problems like separation in the practical situation.

A real venturi is a pipe and therefore an axisymmetric solution is appropriate. Laplace's equation in this case becomes

$$\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2} = 0 \tag{9}$$

where r is the radial coordinate and z is the axial coordinate, respectively. The same separation of variables as in the two-dimensional case becomes as.

$$\psi = f(r)g(z) \tag{10}$$

$$\frac{g''}{g} = -\frac{f''}{f} + \frac{1}{r}\frac{f'}{f} = c \tag{11}$$

Solutions are obtained by the software Mathematica

$$f(r) = A\,rJ_1\left(\sqrt{c}\,r\right) + B\,rY_1\left(\sqrt{c}\,r\right) \tag{12}$$

$$g(z) = Ce^{\sqrt{c}z} + De^{-\sqrt{c}z} \tag{13}$$

where A, B, C, c and D are all constants, J and Y are the Bessel functions of the first and the second kind, respectively. One possible solution is

$$\psi = rJ_1(r)\,e^{-z} \tag{14}$$

The velocity components u_r, u_z and the pressure p become as:

$$u_z = \frac{\partial \psi}{r\partial r} = \left[\frac{J_1(r)}{r} + \frac{1}{2}\{J_0(r) - J_2(r)\}\right]e^{-z} \tag{15}$$

$$u_r = -\frac{\partial \psi}{r\partial z} = J_1(r)\cdot e^{-z} \tag{16}$$

$$p \equiv -u_r^2 - v_z^2 \tag{17}$$

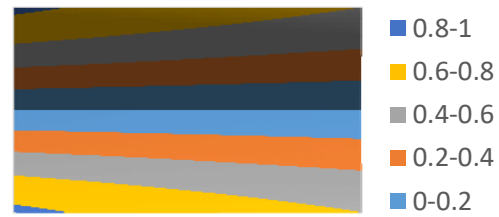

Fig. 8 Two-dimensional nozzle theoretical streamline
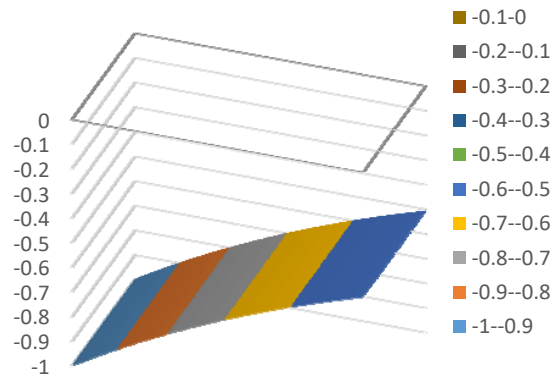$\psi(x, y) = e^{-x} \sin y \quad (0 \le x \le 0.34, 0 \le |y| \le 1)$

Fig. 9 Two-dimensional nozzle theoretical pressure p
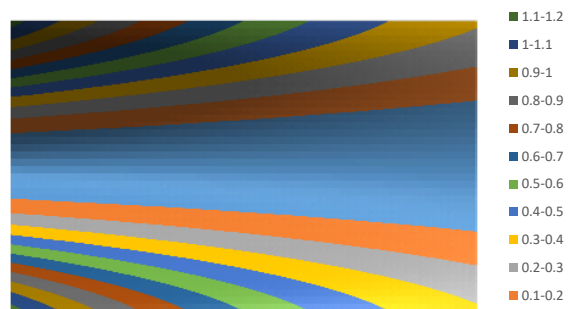$(0 \le x \le 0.34, 0 \le |y| \le 1)$

Fig. 10 Axisymmetric nozzle theoretical streamline
$\psi = rJ_1(r)e^{-z} \quad (0 \le z \le 1.3,\ 0 \le r \le 2)$

Fig. 11 Axisymmetric nozzle theoretical pressure p
$(0 \le z \le 1.3,\ 0 \le r \le 2)$

Fig. 10 shows the stream function ψ, and Fig. 11 shows the pressure p for the axisymmetric case, respectively. These two-dimensional and axisymmetric solutions are mathematically periodic in the y- and the r-directions, respectively. The flow directions are reversible in the solutions, i.e., both diffuser and nozzle flows are possible.

Fig. 12 shows a potential flow stream function through a fictitious axisymmetric orifice with a contraction ratio about 2:1.

The finite difference from of (9) is solved numerically by spreadsheet [5]-[8]. Corresponding pressure is shown in Fig. 13. Real flow is viscous and separates, and also becomes turbulent and unsteady contrary to Figs. 12 and 13.
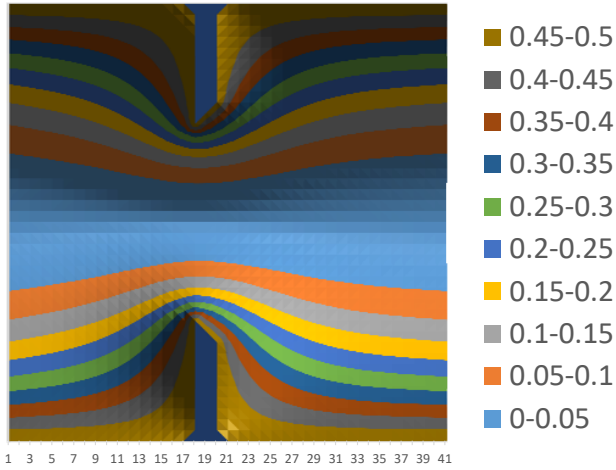

- 0.45-0.5
- 0.4-0.45
- 0.35-0.4
- 0.3-0.35
- 0.25-0.3
- 0.2-0.25
- 0.15-0.2
- 0.1-0.15
- 0.05-0.1
- 0-0.05

Fig. 12 Orifice potential flow stream function ψ

$$\left(0 \leq z \leq 2, 0 \leq r \leq 1\right)$$

- 0-1
- -1-0
- -2--1
- -3--2
- -4--3
- -5--4
- -6--5
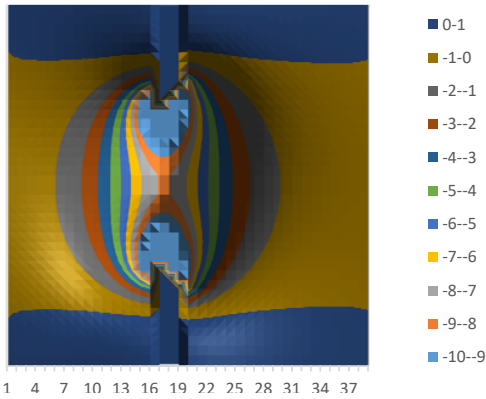- -7--6
- -8--7
- -9--8
- -10--9

Fig. 13 Orifice potential flow pressure distribution p (outer boundary not included) $\left(0 \leq z \leq 2, 0 \leq r \leq 1\right)$

A flow through centrifugal pump impeller is visualized by the vortex singularity method in Fig. 14. The complex potential for the centrifugal pump impeller becomes as [9]-[11].

$$w = \frac{q}{2\pi}\ln z - i\frac{\Gamma_0}{2\pi}\ln z - \sum_{k=1}^{N}\sum_{j=1}^{n+1} i\frac{\Gamma_j}{2\pi}\ln\left(z - z_{k,j}\right) + i\frac{1}{2}r^2\omega \quad (18)$$

where N is the number of impellers, $n+1$ is the number of vortices on each impeller, q is the source strength, i.e., the pump flow rate, $z(= x+iy)$ is the complex number, $z_{k,j}$ is the coordinate of each vortex, Γ_0 is the inlet swirl, Γ_j is the circulation of each vortex, and ω is the angular velocity.

The imaginary part of (18) is the stream function as:

$$\psi = \frac{q}{2\pi}\theta - \frac{\Gamma_0}{2\pi}\ln r - \sum_{k=1}^{N}\sum_{j=1}^{n+1}\frac{\Gamma_j}{2\pi}\ln\left|z - z_{k,j}\right| + \frac{1}{2}r^2\omega \quad (19)$$

where θ is the circumferential coordinate. From (19):

$$w_r = \frac{\partial \psi}{r\partial \theta}$$
$$= \frac{q}{2\pi r} - \sum_{k=1}^{N}\sum_{j=1}^{n+1}\frac{\Gamma_j}{2\pi}\left[\frac{-\left(x - x_{k,j}\right)\sin\theta + \left(y - y_{k,j}\right)\cos\theta}{\left(x - x_{k,j}\right)^2 + \left(y - y_{k,j}\right)^2}\right] \quad (20)$$

$$w_\theta = -\frac{\partial \psi}{\partial r}$$
$$= \frac{\Gamma_0}{2\pi r} + \sum_{k=1}^{N}\sum_{j=1}^{n+1}\frac{\Gamma_j}{2\pi}\frac{\left(x - x_{k,j}\right)\cos\theta + \left(y - y_{k,j}\right)\sin\theta}{\left(x - x_{k,j}\right)^2 + \left(y - y_{k,j}\right)^2} - r\omega \quad (21)$$

where w_r and w_θ are the radial and circumferential relative velocity components, respectively, and

$$\cos\theta \equiv \frac{\partial x}{\partial r} = \frac{\partial y}{r\partial \theta}$$
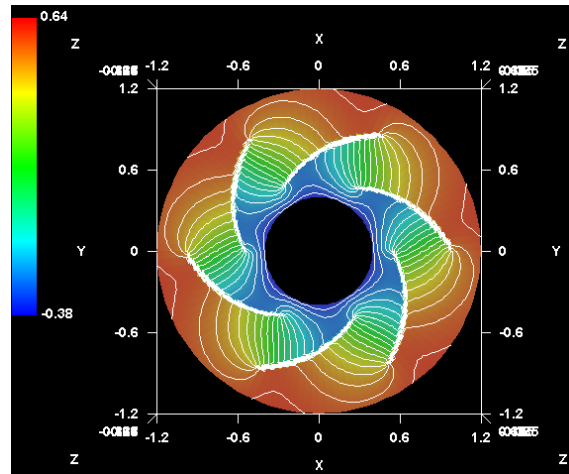$$\sin\theta \equiv \frac{\partial y}{\partial r} = -\frac{\partial x}{r\partial \theta}$$

Fig. 14 Potential flow pressure p through centrifugal pump impeller
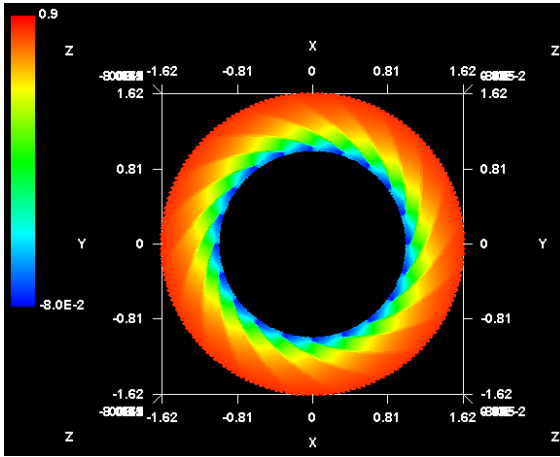$N = 6$, $\beta = \pi/3$, $\phi = 0.24$, $r_1/r_2 = 0.54$

Fig. 15 Potential flow pressure through circular arc diffuser
$N = 20$, $1.04(= r_3 / r_2) \leq r_{\text{diffuser}} / r_2 \leq 1.59(= r_4 / r_2) = 1.59$,
$\alpha = 20°$

A logarithmic spiral for the impeller with the inclination β is given by

$$r = e^{-\tan \beta \cdot \theta} \qquad (22)$$

The flow tangency condition on the impeller becomes

$$\frac{dr}{rd\theta} = \frac{w_r}{w_\theta} = -\tan \beta \qquad (23)$$

From (20), (21) and (23), we get a non-dimensional form of (23) on the impeller collocation point (x_{ci}, y_{ci}) as:

$$\sum_{k=1}^{N} \sum_{j=1}^{n} \frac{\Gamma_j}{2\pi} \left\{ \left[\frac{(x_{ci} - x_{k,j})(\tan \beta \cos \theta + \sin \theta)}{(x_{ci} - x_{k,j})^2 + (y_{ci} - y_{k,j})^2} \right] \right\} \qquad (24)$$

$$= \left(r_{ci} - \frac{\Gamma_0}{2\pi r} \right) \tan \beta - \frac{\phi}{r_{ci}} \quad (1 \leq i \leq n)$$

where

$$x_{ci} \equiv \frac{x_{1,i} + x_{1,i+1}}{2}, \quad y_{ci} \equiv \frac{y_{1,i} + y_{1,i+1}}{2} \qquad (25)$$

$$r_{ci} \equiv \sqrt{x_{ci}^2 + y_{ci}^2} \qquad (26)$$

$$\phi \equiv \frac{q}{2\pi r_2 \cdot (r_2 \omega)} \qquad (27)$$

Although we use the same symbols as those of (18) ~ (23) in (24) ~ (26), the coordinates are divided by the impeller outer radius r_2, the velocities are divided by the impeller tip speed $u_2 = r_2 \omega$, and the circulations are divided by $u_2 r_2$. In (24), we use the Kutta condition as:

$$\Gamma_{n+1} = 0 \qquad (28)$$

Therefore, the summation by j ends at n in (24).

We can solve (24) to get $\Gamma_j (1 \leq j \leq n)$, and therefore determine the velocity components form (20) and (21). Bernoulli's equation for pressure becomes

$$\frac{1}{2}(w_r^2 + w_\theta^2) + p - \frac{1}{2}r^2 = \text{const.} \qquad (29)$$

where the equation is non-dimensional divided by ρu_2^2.

If we omit the last term of the right-hand-side of (18), the equation becomes the complex potential for a stationary diffuser. Similar simultaneous equations are obtained from the flow tangency conditions on the diffuser blades as (24). We can get pressure from Bernoulli's equation in the stationary coordinate. Pressure recovery through circular arc diffuser vanes is shown in Fig. 15. The diffuser vane inclination at the inlet radius r_3 is about 20 degree. Inlet flow angle at the impeller outer radius r_2 is also set $\alpha = 20$ degree, while the circumferential velocity component at the impeller exit is u_2. The diffuser vane geometric parameters are given in [12].

V. CONCLUSION

We introduce the project- and experiment-based fluid dynamics education in Meisei University, Tokyo, Japan. We proposes a traction flight vehicle. This concept is used in the project for the university students and the open campus for nearby pupils. Students get hands-on experience to build the traction flight vehicle and some teaching skills to elementary and junior high school pupils. We test centrifugal pump, triangular weir, venturi, and orifice in the fluid dynamics experiment. Although we learn these devices in the lectures, it is worthwhile for the mechanical engineering students to see how they work in the practical situation.

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