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Effect of Aeration Flow Rate on Improvement of Surface-Piercing Propellers Performance

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P A P E R I N F O

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A B S T R A C T

The Surface-Piercing propeller blades move in and out of the water with each rotation to reduce the immersion depth from the free surface to the shaft axis . The main challenge facing surface piercing propellers, however, is their lower efficiency at lower advance velocity, compared to other propulsion systems. To improve the performance of the propeller, an aeration mechanism was used at low advance velocities so that air was blown to the surface behind the propeller. Experimental studies were carried out on a propeller model in the Hydrotech laboratory of the Iran University of Science and Technology, and the effect of the injected air velocity ratio was evaluated at different immersion ratios. Based on the results obtained, it was concluded that an increase in the injected air velocity ratio could only promote thrust enhancement under specific conditions. For immersion ratios of 0.85 and more, as well as advance coefficients of 0.6 and more, a change in the velocity ratio of the injected air could not lead to an improvement in thrust. The best performance was identified with an immersion ratio of 0.4 and an advance coefficient of 0.4, while thrust performance at below or above of this condition declined .

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NOMENCLATURE

Z	Blade number	U	Velocity
J	Advance coefficient	g	Gravitational acceleration
P/D	Pitch/Diameter ratio	n	Propeller rotational speed
A_E/A_O	Expanded blade area ratio		
P	Pitch	**Greek Symbols**	
Re	Reynolds number	ψ	Shaft angle
W_n	Weber number	γ	Yaw angle
Fr	Froud number	ν	Kinematic viscosity (m^2/s)
Subscripts		σ	Cavitation number
D	Diameter	β	Vertical distance
I	Immersion ratio	α	Horizontal

INTRODUCTION

Surface Piercing Propellers (SPP) belong to a type of shaft-and-propeller propulsion system widely used in recreational craft today. The main operational characteristic of these propellers is their rotation with high angular velocity at the interface between air and water, which means that almost half of the propeller is only submerged. In a propeller rotating cycle, each blade once strikes the water surface and sprays the water, passes through the water, exits into the air until it subsequently sinks into the water. Studies on SPP have mainly focused on evaluating thrust, torque, lateral forces and have included experimental testing alongside some computational studies. In these works, the effects of various parameters such as the immersion ratio, the

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number of blades and the geometric parameters of the propeller (blade cross-section, pitch, rake, skew and so on) on the hydrodynamic characteristics of the propeller were studied.

Among the most outstanding experimental studies in this field, the work of Shiba [1], Hadler and Hecker [2], Hecker [3], Rains [4], Rose and Kruppa [5] and Rose et al. [6] could be noted. Shiba [1] calculated the critical Reynolds number. He saw that the effect of Reynolds number on the performance of propeller decreases above the critical Reynolds number. Hadler and Hecker [2] have shown that the surface-piercing propeller has a higher efficiency under the partial ventilation flow regime, due to the higher lift-to-drag ratio of the blades.

In addition, significant recent experimental research, such as the works by Olofsson [7], Dyson et al. [8] and Peterson [9] examined the performance of surface-piercing propellers and provided further useful information in this regard. For instance, Olofsson [7] in a model-scale laboratory research, studied flow phenomena, as well as average and timed performance of a surface-piercing propeller. He considered the effect of yaw angles, and to a limited extent, the effect of trim angle of the propeller shaft, on hydrodynamic characteristics and flow around the blades for a constant immersion ratio and variable Froude and cavitation numbers. The results showed that a surface-piercing propeller could achieve higher efficiency at an appropriate yaw angle, but resonance of blade vibrations could lead to blade resistance and vibration issues.

Using numerical calculations and other experimental tests Peterson [9] showed that at certain speeds and small yaw angles of the propeller shaft, the efficiency of the surface-piercing propeller could be improved by 3 to 5 percent as the ventilation phenomenon resulting from the suction of air would occur behind the surface of the blade due to the rotation of the propeller at the interface between the air and water.

In another research, Pustoshny et al. [10] published the results of systematic tests on a 5-blade surface-piercing propeller, conducted in a traction tank capable of measuring and recording pressure, and studied the impacts of performance and geometric parameters, including immersion ratio, trim angle, cavitation number and pitch ratio on the hydrodynamic characteristics of the propeller.

Amini et al. [11] studied the effect of aeration on performance of surface-piercing propellers at low advance coefficients. They used an aeration mechanism to inject the air to upstream part of the propeller. Experimental tests were performed in open water conditions. They measured thrust coefficient for different immersion ratios and advance coefficients and reached up to 100% improvement in surface-piercing Propeller's thrust coefficient. They also found out that via increasing immersion ratio, performance improvements can be reached in higher values of advance coefficient.

The flow around the propeller is subject to Navier-Stokes equations and the numerical methods for solving these equations are known as computational fluid dynamics (CFD). These methods include Reynolds Average Navier-Stokes (RANS) Equations, Large Eddy Simulation (LES), Detached Eddy Simulation (DES), and Direct Numerical Simulation (DNS). These methods require extensive computational sources and time to conduct the simulation within a reasonable timeframe, particularly for surface-piercing propellers, whose blades once enter and once exit the water during each rotation cycle. Using the URANS method, Yang et al. [12] investigated the effect of artificially ventilation on the hydrodynamic characteristics of surface-piercing propellers during fully submerged conditions. In this study, the VOF method was employed for modelling the interface of the two phases, and the overlapped mesh technique was used for simulating the rotary motion of the propeller. They have shown that artificial ventilation can increase efficiency at high advance coefficients, but that torque and thrust coefficients. Therefore, propeller efficiency decrease at low advance coefficients.

Gao et al. [13] further employed the URANS method to study the effect of changes in artificial ventilation pipe diameter on the hydrodynamic characteristics of surface-piercing propellers and observed that by increasing the ventilation pipe diameter the thrust and torque coefficients would decrease and the efficiency would gradually increase.

In the present studies, for increase of thrust coefficient of the propeller, the effect of changing the air flow rate injected by the aeration mechanism to the upstream part of the surface-piercing propellers is investigated. For the performance tests of the surface-piercing propeller, an open water tunnel and a test mechanism for the surface-piercing propellers were used at the Hydrotech laboratory of the Iran University of Science and Technology. The tests were conducted on a model propeller at open water conditions. In order to analyze the hydrodynamic behavior of the model propeller, the forces affecting the propeller were identified through the calibration procedure, and the results were obtained in terms of dimensionless propeller thrust coefficient. Using the designed aeration mechanism, air was then injected from the ventilation tube and via horizontal (α) and vertical (β) distances to the model propeller, and the effect of changes in the injected air velocity coefficient ($U' = U_{injected-air}/U_{water}$) was studied for different immersion ratios at low advance coefficients.

HYDRODYNAMIC CHARACTERISTICS OF SURFACE-PIERCING PROPELLERS

Similar to fully-submerged propellers, the performance of surface-piercing propellers is affected by parameters such as blade number (Z), pitch/diameter ratio (P/D), expanded blade area ratio (A_E/A_O), advance coefficient (J), shaft angle (ψ), yaw angle (γ), Reynolds number (Re) and cavitation number (σ). Moreover, the influence of some other parameters must be considered here due to the operation of propeller at the interface between water and air including immersion ratio (I), Weber number (We), and Froude number (Fr). Hence, thrust and torque coefficients for surface-piercing propellers can be expressed as follows [14]:

$$K_{partial-imersed} = f(Z, \frac{P}{D}, Re, F\,r, We, \gamma, \frac{A_E}{A_O}, I, J, \sigma) \quad (1)$$

Through dimensional analysis of fluid dynamics governing equations, several important and effective dimensionless parameters on the flow around ventilated propellers obtained as presented below. So the natural cavitation phenomenon is ignored at this stage.

$I = \frac{H}{D}$	Immersion ratio	(2)
$J = \frac{V}{nD}$	Advance Coefficient	(3)
$Re = \frac{5nD^2(A_E/A_o)}{vZ}$	Reynolds Number	(4)
$Fr = \frac{V}{\sqrt{gD}}$	Froude Number	(5)
$W_n = \sqrt{\frac{\rho n^2 D^3}{\sigma}}$	Weber Number	(6)
$\frac{\beta}{\alpha}$	Ventilation Immersion Ratio	(7)
$U' = \frac{U_{injected-air}}{U_{water}}$	Injected Air Velocity ratio	(8)

In the above equations, V is the advance velocity of propeller (m/s), n is propeller rotational speed (rev/s), D is propeller diameter (m), H is depth of immersion (m), v is the cinematic viscosity of water (m^2/s), g is gravitational acceleration (m^2/s), ρ is water density (kg/m^3), $U_{injected-air}$ is injected air velocity (m/s) which comes from Q_{Air}/A_0 (A_0 is the propeller disc area) and U_{water} is upstream water flow velocity (m/s).

In establishing dynamic and kinematic similarity between real and model propellers, the significant dimensionless numbers for Surface-Piercing Propellers are Froude, Weber, Reynolds, cavitation numbers, advance coefficients and immersion ratio. It is impossible to satisfy similarity conditions for all numbers in a model test. Considering the mentioned limitations and experimental capabilities available, the following requirements were formulated for Re, W_n and Fr numbers:

$$Re \geq 5 \times 10^5 \quad (9)$$

$$W_n \geq 180 \quad (10)$$

$$Fr \geq 4 \quad (11)$$

Under these conditions, the propeller performance curve can be considered as independent of these three parameters [15]. So the trust coefficient for ventilated and non-ventilated conditions will be as follows:

$$K = f(Fr, Re, W_n, I, J, \beta/\alpha, U') \quad \text{Ventilated} \quad (12)$$

$$K = f(Fr, Re, W_n, I, J) \quad \text{Non-Ventilated} \quad (13)$$

EXPERIMENTAL SETUP

For this study, the open water tunnel had an open cross-section of 20×15 centimeters, where the water velocity varied between 2 to 6.5 m/s. The tunnel circuit included a test section, a water pump, a flow meter, a water transfers open channel and a relaxation tank, which supplied the water required in the tunnel and deaerated the water returning from the tunnel. The tunnel also used 4 submerged pumps, located within the relaxation tank, and four pipes connected their outflow by a five-way connector into the main pipe. A by-pass valve was provided at a small distance from the connector, which could regulate the cross-section velocity. Furthermore, there is a magnetic flow meter on the circuit which recorded the average velocity and a connector then connected the circular section to the rectangular section ahead. The flow is further conducted to another rectangular section with a flexible top plate, which could take the shape of the stern of high-speed vessels. Next in the circuit is the open test section for propeller operation. The path continued through an open channel with a wide section, leading back to the relaxation pool, as shown in Figures 1 and 2.

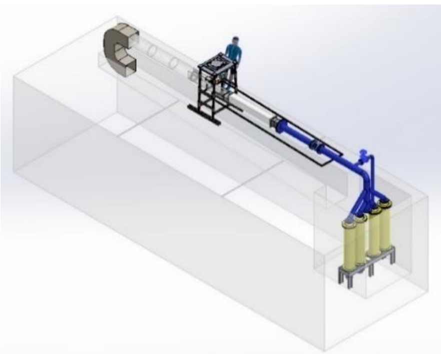

Figure 1. Closed water circuit

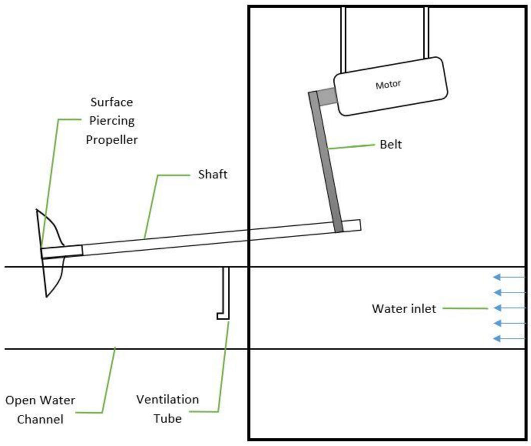

Figure 2. A view of test system and open water circuit [11]

Data collection instruments

The data collection system included a 16-channel data acquisition system, signal conditioners, amplifiers and analog-to-digital signal convertors for the signals from strain gauge outputs. Sampling rate used for the tests is 10000 sample per second. A typical data for thrust signal during 10 seconds is shown in Figure 3.

Model propeller specifications

The following table provides the specifications of the model propeller used for the present study (Table 1). Also the propeller used for experimental study is shown in Figure 4.

Aeration mechanism

In order to improve the performance of the propeller at low advance velocities, an aeration mechanism was implemented using a mechanism designed to blow air towards the upstream part of the propeller with different flow rates. Air is blown through a 4mm diameter pipe, towards the rear of the propeller where cavitation can occur and reduces the wetting area of the upstream portion of the propeller. The schematic view of the surface-piercing propeller and aeration pipe is shown in Figure 5.

Test plan matrix

According to the defined criteria and ranges for model similarity in current work, the propeller rotational speed for a 130 mm model diameter should be between 1500 and 3000 rpm and the advance velocity should be calculated based on each water velocity. Due to the limited water velocity in the open water circuit, not all advance coefficients can be regulated by the advance velocity alone. Therefore, to establish the required advance coefficients for $0.2 \leq J \leq 0.6$, it was necessary to also consider the water advance velocity as a variable parameter. A total of 108 (6×6×3) tests were performed as test plan matrix Table 2, including ventilation tests at 6 immersion ratios; $I= H/D$ (I= 0.25, 0.4, 0.6, 0.75, 0.85, 1), 6 advance coefficients; $J= V/nD$ (J= 0.2, 0.25, 0.35, 0.4, 0.45, 0.6) and 3 injected air velocity ratios; U' (U'_1= 0.041, 0.082, 0.123)

Table 1. Model propeller specifications

Diameter of propeller (mm)	Diameter of the hub (mm)	Pitch at the radius of 0.7D (mm)	Number of blades
130	44	162	4

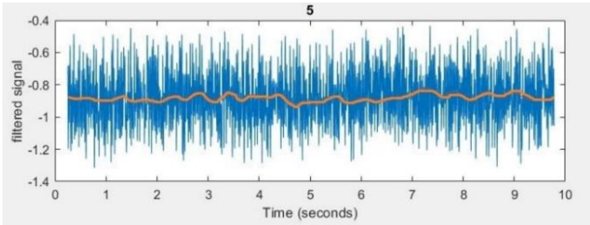

Figure 3. A typical data for thrust signal during 10 seconds

Figure 4. Model propeller

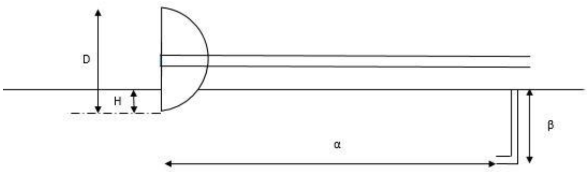

Figure 5. Schematic view of the surface-piercing propeller and aeration pipe

RESULTS AND DISCUSSION

The effect of changes in injected air velocity ratio at different immersion ratios and different advance coefficients was investigated. 0 6 illustrates the horizontal axis stands for immersion ratio and the vertical

Table 2. Tests Plan matrix for total number of 108 test

I_i (i= 1,2,3,4,5,6)	U'_j (j=1,2,3)	J_k (k= 1,2,3,4,5,6)
I_1=0.25		J_1= 0.2
I_2=0.4	U'_1= 0.041	J_2= 0.25
I_3=0.6	U'_2= 0.082	J_3= 0.35
I_4=0.75	U'_3= 0.123	J_4= 0.4
I_5=0.85		J_5= 0.45
I_6=1		J_6= 0.6

axis for thrust coefficient improvement $\left(\frac{100\times(K_{t,ventilated}-K_{t,unventilated})}{K_{t,unventilated}}\right)$. 0 7 demonstrates the horizontal axis stands for injeted air velocity ratio and the vertical axis for thrust coefficient improvement, while each group of data stand for special immersion ratio. It is evident from the graphs that:

1. Increasing the injected air velocity ratio increased the percentage improvement in propeller thrust coefficient for different immersion ratios. In fact, the thrust coefficient at the operating points of the propeller increased with higher injected air velocity ratio for different immersion coefficients;
2. For immersion ratios greater than 0.85, the modification of the injected air velocity ratio did not affect the improvement in the thrust coefficient of the propeller;
3. An immersion ratio of 0.4 or less provided the greatest performance improvement, while an immersion ratio of up to 0.85 were less affected by changes in injected air velocity ratio. Moreover, the immersion ratio of 0.4 and the injected air velocity ratio of 0.123 resulted in the greatest performance improvement.

The effect of different injected air velocity ratio and advance coefficients on thrust coefficient improvement is presented in Figures 8 and 9. The vertical axis is thrust coefficient improvement and the horizontal axis represents the advance coefficient in Figure 8 and the injected air velocity ratio in Figure 9. The results reported are the average of all tests performed. The graphs show that:

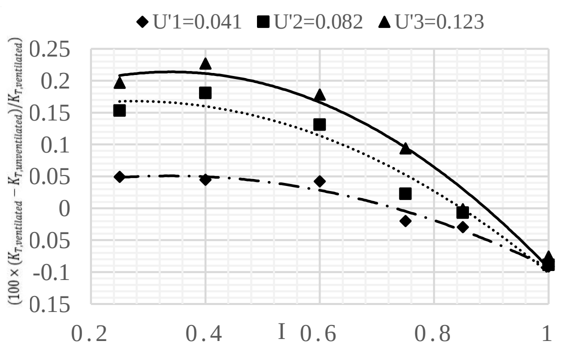

Figure 6. Thrust Coefficient Improvement versus Immersion Ratios for different injected air velocity ratio

4. In general, the higher injected air velocity ratio is correlated with a higher percentage improvement of propeller thrust coefficient for all advance coefficients. In fact, the thrust coefficient at all propeller operating points increased with higher injected air velocity ratio for different advance coefficients;
5. For low advance coefficients (0.2 to 0.4), the improvement in the thrust coefficient tends upwards and reaches 17% at advance coefficients of 0.4. The improvement in the thrust coefficient then experiences a downward trend for the advance coefficients between 0.45 and 0.6, while the variation in the injected air velocity ratio does not affect the improvement of propeller performance for advance coefficients greater than 0.6. In addition, the injected air velocity coefficient of 0.123 at advance coefficient of 0.4 results in the highest performance improvement;
6. Ventilation at all injected air velocity ratio for advance coefficients greater or less than an optimum value of the order of 0.4 reduces propeller thrust performance. In fact, the changes in the injected air velocity ratio led to an optimal condition for aeration.

Using the results obtained from the experimental study, one could conclude that under special conditions only effective aeration could be achieved, which is schematically shown in Figure 10 The obtained data were experimentally evaluated and illustrated in Figure 11. It is obvious that the injected air at a higher advance velocity does not touch the tips of the propellers due to

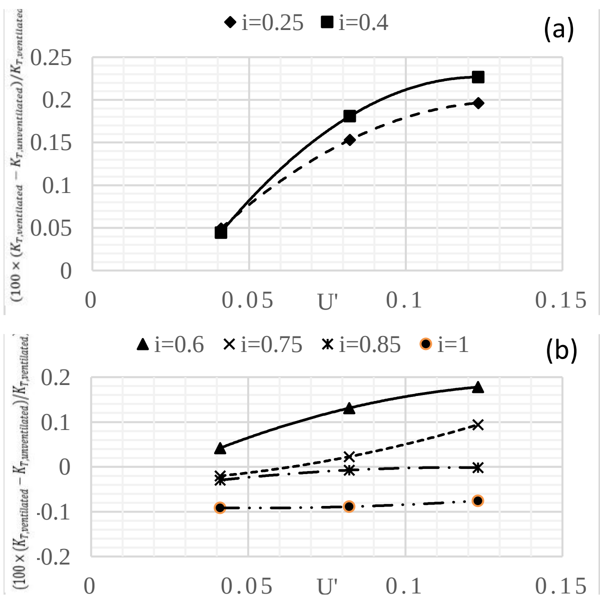

Figure 7. Thrust Coefficient Improvement versus Injected Air Velocity ratio for different Immersion ratios (a) i=0.25, 0.4 and (b) i=0.6, 0.75, 0.85 and i=1

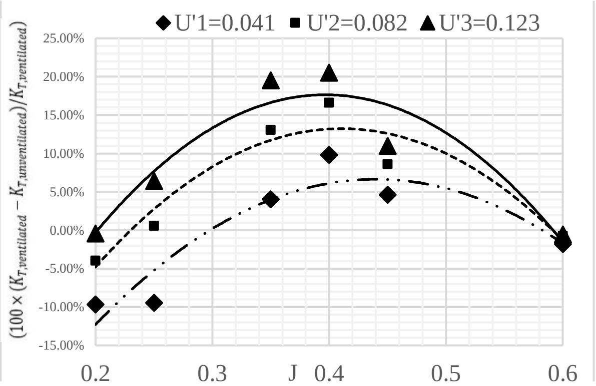

Figure 8. Thrust Coefficient Improvement versus Advance Coefficient for different injected Air Velocity ratio

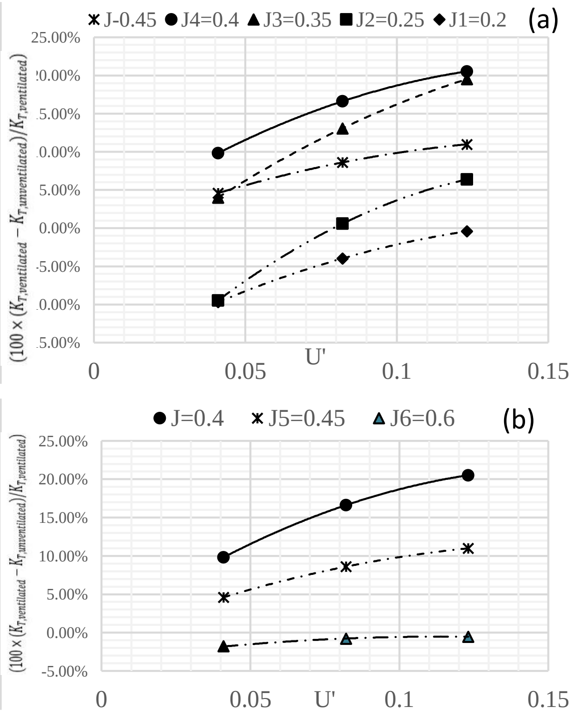

Figure 9. Thrust Coefficient Improvement versus Injected Air Velocity ratio for different Advances Coefficients (a) j=0.2, 0.25, 0.35 and j=0.4 and (b) j=0.4, 0.45 and j=0.6

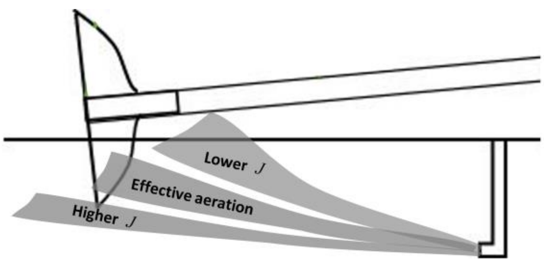

Figure 10. Schematic representation of effective aeration

Figure 11. Effective Aeration test at U' =0.123; β =70 mm

the dominance of the inertia of the water flow. On the other hand, at a lower advance velocity, the injected air also does not touch the propeller due to the dominance of air buoyancy.

CONCLUSION

Compared to other propulsion systems, surface-piercing propellers have lower efficiency at low advance velocities, until the vessel reaches a higher velocity and the propeller delivers its best performance. In an innovative approach, the present study investigated the effect of changing the velocity ratio of the injected air on the upstream part of a surface-piercing propeller in order to improve the thrust coefficient. The effect of the injected air velocity ratio as a parameter was studied on different advance coefficients and immersion ratios. Based on the results obtained, it was concluded that increasing the injected air velocity ratio could only promote thrust enhancement under specific conditions. For immersion ratios of 0.85 and more, as well as advance coefficients of 0.6 and more, a change in the velocity ratio of the injected air could not lead to an improvement in thrust. The best performance was identified with an immersion ratio of 0.4 and an advance coefficient of 0.4, while thrust performance at below or above this condition declined. The injected air at a higher advance velocity does not touch the tips of the propellers due to the dominance of the inertia of the water flow. On the other hand, at a lower advance velocity, the injected air also does not touch the propeller due to the dominance of air buoyancy.

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CONFLICT OF INTEREST

Authors declare that they have no conflict of interest.

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Persian Abstract

چکیده

پروانه نیمه مغروق به پروانه‌ای گفته می‌شود که در حین چرخش، پره‌های آن از آب بیرون آمده و دوباره وارد آب می‌شوند، به طوری که عمق فرورفتگی از سطح آزاد سیال تا خط مرکزی شفت حتی تا صفر می‌تواند کاهش یابد. این یعنی نیمی از پروانه به طور کامل در آب و نیمی دیگر به طور کامل خارج از آب قرار دارد. چالش اصلی پیش روی پروانه‌های نیمه مغروق، راندمان پایین تر آنها در سرعت پیشروی کمتر، در مقایسه با سایر سیستم‌های پیشران است. برای بهبود عملکرد ملخ، از مکانیزم هوادهی در سرعت‌های کم پیشروی استفاده شد تا هوا به سطح پشت ملخ دمیده شود. مطالعات تجربی بر روی یک مدل پروانه در آزمایشگاه هیدروتک دانشگاه علم و صنعت ایران انجام شد و تأثیر نسبت سرعت هوای تزریقی در نسبت‌های غوطه‌وری مختلف مورد ارزیابی قرار گرفت. بر اساس نتایج به‌دست‌آمده نتیجه‌گیری شد که افزایش نسبت سرعت هوای تزریقی تنها می‌تواند باعث افزایش رانش در شرایط خاص شود. برای نسبت‌های غوطه‌وری ۰/۸۵ و بیشتر و همچنین ضرایب پیشروی ۰/۶ و بیشتر، تغییر در نسبت سرعت هوای تزریق شده نمی‌تواند منجر به بهبود رانش شود. بهترین عملکرد با نسبت غوطه‌وری ۰/۴ و ضریب پیشروی ۰/۴ شناسایی شد، در حالی که عملکرد رانش در زیر یا بالاتر از این شرایط کاهش یافت.