Study on the influence of pumping system on the hydrodynamic performance of air tanker

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Abstract. The influence of the pumping system on the hydrodynamic performance of the air tanker were investigated in this paper. The hydrodynamic performance of the air tanker with different displacements under the different Froude numbers was studied by experimental method. RANS methods and overset mesh were used to compute the viscous flow field of an air tanker under three conditions at different Froude numbers. Numerical method adopted in this paper was verified and validated by comparing the experimental results with the simulation results. The experimental results showed that the total resistance and the heave amplitude of air tanker with different displacements increased, while the pitch angle decreased, as the speed increased. And the larger the displacement, the greater the total resistance, pitch angle and heave amplitude. The simulation results showed that the drainage efficiency, the load of the baler and the additional pitching moment showed non-linear growth with increasing speed. As the baler lowered, the total resistance and heave amplitude of the aircraft increased, but the pitch reduced. The effect on the hydrodynamic performance of air tanker was not obvious as the baler closed.

Keywords: air tanker; baler; drainage efficiency; hydrodynamic performance; RANS method

1. Introduction
The involvement of large amphibious aircraft in forest aerial extinguishing has many advantages over traditional firefighting methods: such as strong maneuverability, fast arrival, and large water carrying capacity [1]. After years of research and practice, experts and scholars have completed the series of works of fire-fighting, and achieved remarkable results in practical applications. Mottard (1959) studied the effects of waves on the resistance of seaplanes during take-off [2]. Yongliang Wang (2012) obtained the mathematical model of the water injection algorithm based on the principle of continuous method of calculating the hit point bombs ballistic solver [3]. Huang Sen (2015) conducted an in-depth study on the wave experiment technology of the amphibious aircraft model, the motion response of the aircraft on the waves, and the hydrodynamic torque characteristics of the hull[4] [5]. Xupeng Duan (2019) studied the air and hydrodynamic performance of seaplane mooring based on CFD method [6].
According to the design requirements of pumping system of the air tanker, the following research was carried out. The law of the resistance and attitude of the air tanker with different displacements as the baler lowered was investigated by conducting the experiment. Some researchers conducted by numerical simulation were including the law of drainage efficiency and load of the baler with the speed, the hydrodynamic characteristics of air tanker under three conditions of no, closed and lowered the baler.

2. Geometry and Condition

The conditions of the experiment and simulation carried out in this paper were shown in table 1. The changes in the drainage system were divided into three conditions: non-baler, closed baler and lowered baler. The model of air tanker was shown in figure 1. The typical features of the baler were shown in figure 2.

| Condition | Load     | Baler     | Speed (m/s) | Method |
|-----------|----------|-----------|-------------|--------|
| 1         | 0.79Δa   | lowered   | 8, 9, 10, 11, 12, 13 | EFD    |
| 2         | 0.85Δa   | lowered   | 8, 9, 10, 11, 12, 13 | EFD    |
| 3         | Δa       | lowered   | 8, 9, 10, 11, 12, 13 | EFD    |
| 4         | Δa       | -         | 8, 9, 10, 11, 12   | CFD    |
| 5         | Δa       | closed    | 8, 9, 10, 11, 12   | CFD    |
| 6         | Δa       | lowered   | 8, 9, 10, 11, 12, 13 | CFD    |

3. Experiment

3.1. Design of experiment

Unlike actual air tanker, the water flow of the baler discharged to the outside of the model through the water drain pipe instead of flowing into the water tank during the experiment. And a certain weight of water was injected into the water tank through the drain pipe before the trailer drove. The experiments were carried out on the overhang device of the trailer. The experiment equipment mainly included the trailer, the overhang device, the motion device and the inhibiting device. The overhang device was shown in figure 3.
3.2. Experimental data
The experimental results of conditions 1-3 were shown in figure 4 and figure 5. As the speed increased, the total drag and the heave increased, while the pitch decreased. The larger the amount of water, the greater the total drag, the pitch and the heave amplitude.

![Figure 4. Total drag at different conditions.](image1)
![Figure 5. Pitch angle (a) and heave amplitude (b) at different conditions.](image2)

4. Numerical simulation

4.1. Mesh generation and boundary condition
A trimmed cell mesher was employed to produce a high-quality grid for complex mesh generating problems. The refined mesh density in these zones was achieved by using volumetric controls applied to these areas. The overset mesh was adopted to simulate the seaplane movement. The most refined mesh areas around the hull remained within the boundaries of the overset domain. The mesh generation was shown in figure 6(a). The boundary conditions were shown in figure 6(b). The inlet, side, top and bottom boundaries were both selected as velocity-inlet. The outlet was selected as pressure-outlet. The symmetry plane had a symmetry condition.

The turbulence model was SST k-ω model [7], and the average value of wall Y+ adopted in this paper was within 1. The two-phase Volume of Fluid (VOF) technique was adopted for capturing the free surface.

![Figure 6. Mesh distributions of seaplane (a) and the applied boundary conditions (b).](image3)

4.2. validation and verification
The results of total drag, pitch angle and heave amplitude observed from numerical simulations and experiments were shown in figure 7(a) and (b). In all, the simulation results were close to the experimental data, which confirmed the applicability and rationality of grid distributions and turbulence model adopted in this paper.
5. Results and Discussion

5.1. Drainage Efficiency and Load

Generally, the specified amount of water intake within the particular time need to be completed for air tanker. Therefore, the law of the drainage efficiency of pumping system with the speed was analyzed in this paper by computed the flow rate of the baler. The flow rate \( Q: \text{kg/s} \) of the baler increased with the increase of the speed, and the relationship of which was non-linear as shown in figure 8. The quadratic polynomial function was used to fit the flow rate of the baler.

\[
Q = -0.015V^2 + 0.596V - 1.841 \quad (Q:\text{kg/s}, V:\text{m/s}) \tag{1}
\]

Comparing the computed and fitted values, it could be found that the relationship between the flow rate of the baler and speed was accurately fitted by quadratic function (1). The distributions of volume fraction of the entrance of the baler at speed of 8m/s and 13m/s were shown in figure 9, from which we observed that the immersion area of the baler varied with the speed. Therefore, as the speed increased, the drainage efficiency of the water intake system was not proportional with the speed.

During the process of pumping, the force of the baler and the additional pitching moment generated by the pumping system should be paid attention to avoiding structural damage or the air tanker out of control while the efficiency of water intake system was satisfied. It could be observed from figure 10 that the distribution of pressure inside the baler was obviously larger than that outside the baler. The force of the baler could be decomposed into horizontal stern and vertical downward force. Figure 11(a) and figure 11(b) showed that the force of baler and additional pitching moment generated by the whole pumping system increased as the speed increased obviously for lowered baler, while little change for closed baler, comparing non-balers. Figure 11(a) showed that the horizontal stern and vertical downward force increased as the speed increased obviously for lowered baler, while little change for closed baler, comparing non-balers. Figure 11(b) showed that the additional pitching moment generated by the whole pumping system on the fuselage increased nonlinearly with the increase of the speed when the baler was lowered. With the increase of the speed, the growth rate of additional pitching moment increased
obviously. Therefore, the additional pitching moment caused by the baler should be taken into account in the design of the pumping system.

![Figure 10. Pressure distribution of baler at the speed of 13m/s.](image)

![Figure 11. Fx, Fz(a) and moment(b) at the condition 5 and 6.](image)

5.2. Effect of Baler on Resistance

The variation of dimensionless total drag coefficient at different speed under the condition 4-6 was shown in figure 12(a). Figure 12(a) showed that the total drag decreased firstly, then increased with the increase of the speed for no-baler and closed baler, and the variation of which was small. The total drag increased approximately quadratic curve with the increase of speed for lowered baler. The variation of growth rate of total drag with the increase of the speed under condition 4 and 5 was from 2.6% to 6% for closed baler, while 47% to 95.7% for lowered baler as shown in figure 12(b). When the baler was closed, the total drag of the air tanker increased slightly, while the total drag increased obviously when the suction bucket was lowered.

![Figure 12. Variation of total drag (a) and error of total drag(b) with the increasing speed.](image)

5.3. Effect of Baler on Stability

Figure 13(a) showed the variation of the pitch angle of the air tanker with the speed under the condition 4-6. As shown in figure 13, the pitch angle of the air tanker decreased with the increase of the speed in all conditions. The difference between the pitch angle of the closed baler and the non-baler was very small, while the pitch angle of the lowered baler was obviously smaller than the other two conditions. The additional pitching moment produced by the pumping system (as shown in figure 11(b)) restrained the tail inclination of the fuselage when the baler was lowered, so the pitching angle amplitude was obviously smaller. The additional pitching moment produced by the pumping system was very small when the baler was closed, so there was little difference of the trim angle between the closed baler and the non-baler.

Figure 13(b) showed the variation of heave amplitude of the fuselage with the increase of speed in three conditions. The heave amplitude of fuselage increased with the increase of the speed in all three cases. There was little difference of the heave amplitude between the closed baler and non-baler. The heave amplitude was similar for closed baler and non-baler, but the heave amplitude for closed baler
was obviously larger than that of the other two conditions. By analyzing the force exerted on the whole pumping system, it was found that lift force was about 0.3%Δ under the condition of closed baler and 5%Δ for lowered baler, respectively.

![Figure 13](image13.png)

**Figure 13.** Variation of Pitch (a) and heave/L (b) with the increasing speed at different conditions.

Computed and experimental results of the attitude and free surface distribution of air tanker for lowered baler at the speed of 8 m/s and 13 m/s were shown in figure 14 and 15 respectively. From the computed results, with the increase of speed, the computed Kelvin angle decreased, and the wave amplitude decreased because the immersion depth of the air tanker decreased. The speed of water injection at the outlet of the water intake system increased. The experimental results in figure 8 was in good agreement with the variation of free surface computed by CFD. At the same time, the computed results of resistance and attitude were consistent with the experimental results. In conclusion, it was reasonable and feasible to simulate the viscous flow around a high-speed object by CFD method.

![Figure 14](image14.png)

**Figure 14.** Computed free surface around seaplane at speed of 8 m/s (a) and 13 m/s (b)

![Figure 15](image15.png)

**Figure 15.** Experimental tests at speed of 8 m/s (a) and 13 m/s (b)

6. **Conclusion**

Experiment and CFD simulation were conducted in this paper to study the flow field as well as hydrodynamic properties for large fire-fighting amphibious aircraft. From the results of these works, the following conclusions could be derived:

1. The experimental results showed that the total resistance and the heave amplitude of aircraft with different displacements increased with the increase of the speed, while of which the pitch angle
decreased with the increase of the speed. And the larger displacements, the greater the total resistance, trim angle and heave amplitude.

2. The flow rate of the bucket increased with the increase of the speed. The quadratic function can well fit the relationship between the flow rate and the speed. The load and the additional pitching moment produced by pumping system increased with the increase of the speed for lowered baler.

3. When the baler was lowered, the total drag of the air tanker increased obviously. Meanwhile, the heave amplitude increased and the pitch angle decreased.

4. Comparing the experimental results with the computed results, it showed that the CFD method was reasonable and feasible to simulate the viscous flow field around a high-speed object.

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