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Numerical investigation of thermal wake evolution behind an underwater vehicle in stratified flow

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Abstract. To investigate the evolution characteristics of the thermal wake generated by an underwater vehicle in stratified flow, a three-dimensional numerical model is established. Under the Boussinesq approximation, the governing equations of the flow field and the temperature transport equation are solved in a coupled manner. The ambient stratification is prescribed according to the vertical temperature profile of the background seawater. The results show that background stratification significantly suppresses the vertical diffusion of the wake, causing the thermal wake to develop mainly along the streamwise direction. Propeller rotation and wake entrainment alter the local temperature distribution in the wake region and generate a distinct temperature-anomaly structure. The temperature anomaly continues to develop in the near wake, reaches its peak intensity at a certain downstream location, and then gradually decays due to diffusion. The present study provides useful support for thermal-signature prediction and wake identification of underwater vehicles in complex ocean environments.

1. Introduction

An underwater vehicle generates a complex wake during navigation, and the wake contains various physical quantities, including velocity, pressure, vorticity, and temperature. These characteristics make it an important subject in underwater target detection. Unlike a homogeneous fluid, the real ocean environment usually exhibits obvious temperature and density stratification [1]. Especially in thermocline regions, background stratification can significantly suppress vertical mixing, thereby changing the propagation, diffusion, and attenuation processes of the wake [2]. Therefore, investigating the formation and evolution of thermal wakes behind underwater vehicles in stratified flow is of great significance for understanding the multiphysics coupling mechanisms of wakes in complex ocean environments.

In recent years, extensive studies have been carried out on underwater-vehicle wakes, mainly focusing on hydrodynamic wake evolution [3], free-surface response [4, 5], and thermal wake characteristics. Existing studies have shown that background stratification can significantly influence the evolution of wake vortical structures and alter the spatial pattern, scale distribution, and persistence of the wake. Meanwhile, the thermal wake, as an important non-acoustic signature, has also attracted increasing attention [6]. Considerable efforts have been made to study the propagation of thermal wakes in homogeneous flow [7], the evolution of thermal characteristics near the free surface [8], and the interaction between the wake and the temperature field. A recent review by Cao et al. [9] comprehensively summarized the evolutionary characteristics of hydrodynamic and thermodynamic wakes in linearly stratified fluids and highlighted the importance of coupled wake propagation and multiphysics interactions. Cao et al. [4] further showed that continuous stratification can significantly modify the wake structure and hydrodynamic behavior of a generic submarine operating near the free surface. In terms of thermal signatures, Luo et al. [10] experimentally investigated the surface thermal wake generated by a submerged vehicle and quantified the effects of environmental and operating conditions on the wake characteristics. Wang et al. further examined the surface thermal characteristics during vehicle acceleration and showed that stratification and submergence depth strongly affect the observable thermal pattern [11]. However, compared with the homogeneous-flow condition, the coupled mechanisms of the wake flow and temperature field behind an underwater vehicle in a stratified environment remain insufficiently understood. In particular, the formation mechanism, spatial distribution, and downstream evolution of temperature anomalies under the combined effects of propeller-wake entrainment and ambient thermal stratification are still unclear.

To address this issue, a three-dimensional numerical model is established in this study to investigate the thermal wake behind an underwater vehicle in stratified flow. The SUBOFF hull equipped with an E1618 propeller was employed as the study model. Under the condition of background seawater temperature stratification, the temperature-field distribution and its evolution in the wake region are analyzed. The effects of stratification on the wake temperature-anomaly structure, wake propagation pattern, and downstream development are discussed. The formation and evolution mechanisms of the thermal wake under the combined effects of propeller-wake entrainment, stratification suppression, and thermal diffusion are also revealed.

2. Numerical method

2.1. Governing equations

The present study focuses on the thermal wake generated by an underwater vehicle in a stratified environment. The fluid medium is treated as single-phase incompressible seawater, and the evolution of the thermal wake is determined by the coupling of the flow field and the temperature field. The governing equations include the continuity equation, momentum equation, and energy equation.

For an incompressible fluid, the continuity equation can be written as

$$\frac{\partial u_i}{\partial x_i} = 0$$

The momentum equation is expressed as

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(2\mu S_{ij}) + \rho g_i - \frac{\partial \sigma_{ij}}{\partial x_j}$$

where p is the pressure, μ is the dynamic viscosity, g_i is the component of gravitational acceleration, S_{ij} is the strain-rate tensor, and σ_{ij} denotes the Reynolds stress term. The SST k-ω turbulence model is adopted in the present study. This model is selected because the wake behind a propeller-driven underwater vehicle involves the interaction of near-wall boundary layers and strong shear layers in the propeller slipstream. Compared with the standard k-ε model, the SST k-ω model generally provides better robustness for near-wall flow and separated-flow prediction, while retaining reduced sensitivity to free-stream conditions.

Considering that the evolution of the temperature field is mainly governed by fluid convection and heat conduction, while no additional volumetric heat source, phase change, or chemical reaction is considered, the energy equation can be written as

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right)$$

where h is the specific enthalpy, λ includes both molecular and turbulent thermal diffusion, and T is the temperature. For incompressible seawater under constant-pressure specific-heat conditions, the enthalpy is given by $h = c_p T$. The above governing equations jointly describe the coupled evolution of the velocity field and the temperature field in the wake region of an underwater vehicle in stratified flow.

2.2. Computational setup

The SUBOFF model is selected as the underwater vehicle model, and it is enlarged by a factor of 24. The computational domain is a three-dimensional cuboid, and the longitudinal axis of the vehicle is aligned with the incoming-flow direction. To reduce the influence of the boundaries on wake development, the computational domain is set as follows: $1L$ upstream of the vehicle, $10L$ downstream, $2L$ on each lateral side, and $4D$ in both the upper and lower directions, where L is the vehicle length and D is the characteristic diameter of the vehicle, as shown in Figure 1.

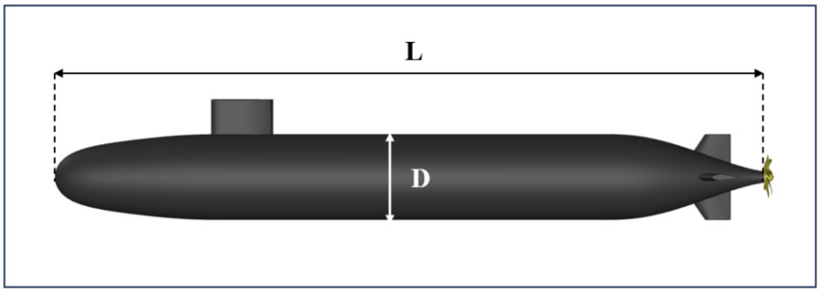

Figure 1. Underwater vehicle model.

The inlet boundary is specified as a velocity inlet, with an incoming-flow velocity of 3.051 m/s, and the propeller rotational speed is set to 0.57 rps. The outlet boundary is defined as a pressure outlet. The surface of the underwater vehicle is treated as a no-slip moving wall, while the upper, lower, and side boundaries are set as wall boundaries. The background seawater temperature is prescribed in a stratified form, and its vertical variation is shown in Figure 2. It can be seen that the seawater temperature gradually decreases with increasing depth, showing a clear stratified structure, with a relatively high temperature near the surface, a lower temperature in deeper regions, and an obvious thermocline in the middle layer. This temperature stratification provides the initial thermal environment for the evolution of the thermal wake.

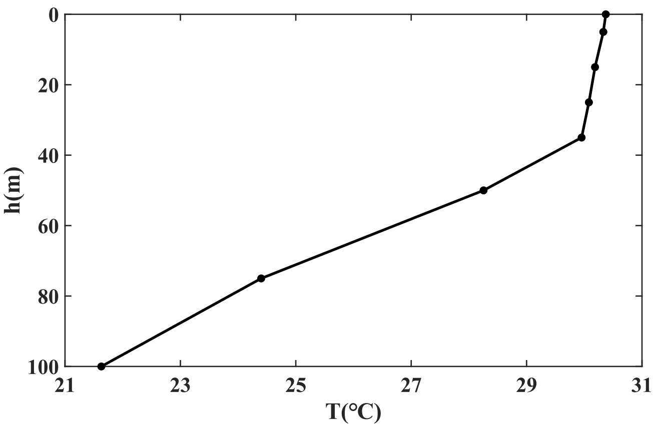

Figure 2. Vertical temperature profile of the stratified ambient seawater.

3. Results and discussion

Figure 3 shows the temperature distribution on the longitudinal symmetry plane of the underwater vehicle. It can be seen that, in the stratified background environment, a distinct wake region is formed behind the vehicle after it passes, and the local isotherms are significantly disturbed. The wake mainly extends along the streamwise direction, whereas its vertical spread is relatively limited, indicating that the stratified environment has a clear suppressing effect on the vertical diffusion of the thermal wake. From the overall morphology, the thermal wake exhibits a slender band-like structure and persists over a long downstream distance, demonstrating strong anisotropic development. This indicates that, in stratified flow, the evolution of the thermal wake is not a simple three-dimensional uniform diffusion process, but is constrained by ambient stratification and develops primarily along the main flow direction.

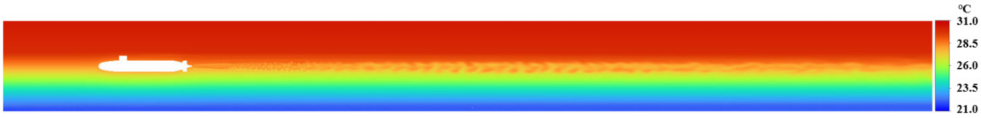

Figure 3. Temperature distribution on the longitudinal symmetry plane of the underwater vehicle wake.

Figure 4 further illustrates the temperature-anomaly distribution in the wake. A distinct low-temperature band is formed behind the vehicle, and the temperature at the wake center differs from the ambient temperature at the same depth. Meanwhile, the wake continues to extend downstream. This occurs because the velocity-deficit region and the vortex structures generated in the wake induce entrainment of the surrounding fluid, especially drawing colder fluid from deeper water layers into the wake core. This process forms a relatively low-temperature anomaly along the wake center. At the same time, some wavy structures can still be observed in the near wake, indicating that the tail vortices remain relatively strong in the early stage of wake development and dominate temperature transport.

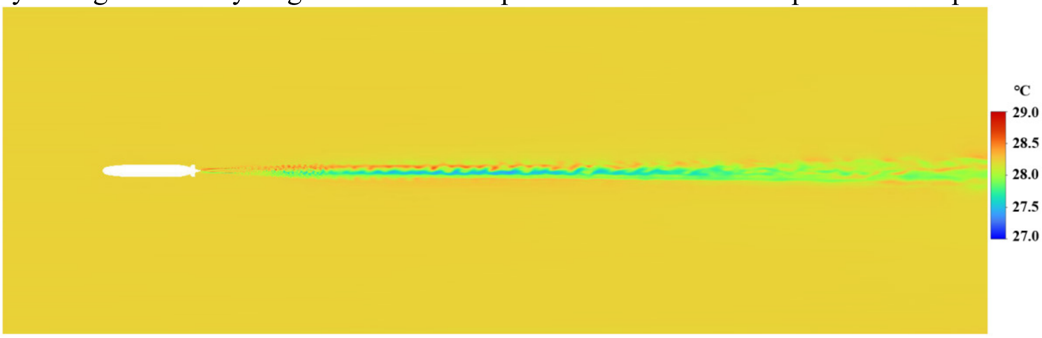

Figure 4. Temperature-anomaly distribution in the wake region behind the underwater vehicle.

To further analyze the downstream evolution of the thermal wake, Figure 5 presents the transverse temperature distributions at four downstream sections, namely $x = 1L$, $3L$, $5L$, and $7L$. It can be seen that a distinct temperature minimum appears near the wake center at all sections, and the temperature gradually recovers to the background value away from the centerline.

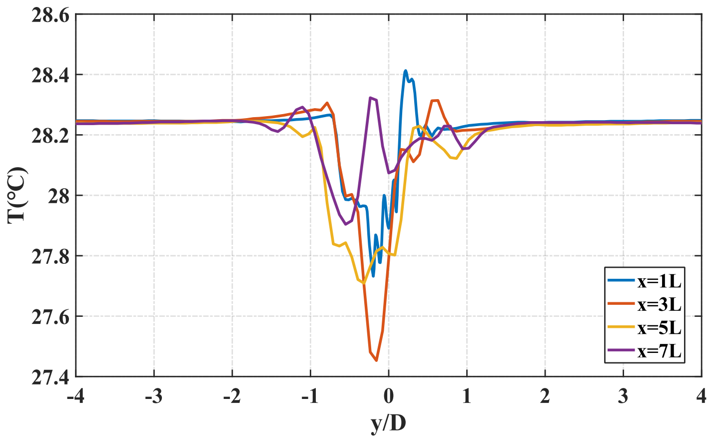

Figure 5. Transverse temperature distributions at different downstream sections.

At $x = 1L$, the wake-induced temperature variation has initially formed, but the affected region is still relatively narrow, indicating that the wake-mixing effect starts to modify the local temperature structure shortly after the vehicle passes. At $x = 3L$, the central temperature reaches its minimum value of approximately 27.45 °C, showing that the wake temperature anomaly does not decay immediately in the near wake but continues to intensify within a certain downstream distance. This indicates that the vortical structures in the near wake still have relatively strong entrainment capability and continuously transport fluid with different temperatures into the wake core, thereby strengthening the temperature variation. As the wake propagates further downstream to $x = 5L$ and $x = 7L$, the central temperature anomaly gradually weakens, while the lateral influence range increases and the temperature profile becomes smoother. This suggests that, with downstream development, the coherent vortical structures gradually decay and the temperature field becomes increasingly dominated by turbulent diffusion and heat conduction. Consequently, the wake evolves from a locally strong and narrow anomaly in the near wake into a weak and broad diffusive anomaly in the far wake. In addition, slight temperature recovery appears on both sides of the wake center in some curves, indicating that the transverse transport process is not a simple single-peak diffusion process, but is affected by the complex lateral redistribution induced by wake vortices.

4. Conclusion

This study numerically investigates the evolution characteristics of the thermal wake behind an underwater vehicle in stratified flow. The results show that background stratification suppresses the vertical diffusion of the wake and causes the thermal wake to develop mainly along the streamwise direction. The propeller rotation and wake entrainment alter the local temperature distribution in the wake region and generate a distinct temperature variation. The wake temperature anomaly continues to intensify in the near wake, and then gradually decays and diffuses downstream, while the affected region becomes wider. Overall, the formation and evolution of the thermal wake in stratified flow are jointly governed by vortex entrainment, stratification suppression, and turbulent diffusion.

These findings improve the understanding of thermal-wake evolution in stratified environments and provide useful support for the prediction and identification of underwater thermal signatures. Nevertheless, the present model is based on the SST k-ω RANS approach and does not include free-surface effects, which may limit its capability in resolving near-wake unsteady vortical structures and more realistic ocean conditions. Future work will therefore focus on higher-fidelity simulations and extended environmental modelling.

Acknowledgments

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