Sheltering of sea ice ridges in the ice-ocean drag force: implications from laboratory experiments

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Abstract

The increasing movement and deformation of Arctic sea ice cover results in pronounced drag sheltering effects behind sea ice pressure ridges. This needs to be accounted for in the parameterization of the form drag of ridges, thereby posing a challenge to evaluate the ice–ocean dynamic feedback. Laboratory experiments were conducted in a water tank to explore the sheltering effect between adjacent ridges of various geometries. The form drag forces on the keel models were measured, and the particle image velocimetry (PIV) system was employed to capture the flow fields surrounding the models to explain the variations in the drag force. The key sheltering parameters were the ratio between keel spacing and keel depth L/H, flow velocity u, and keel slope angle α. The results showed that the drag force F1 on the upstream keel was close to the value of the single keel case, while the drag force F2 on the downstream keel was lower, for L/H [?] 10 even opposite to the flow direction. Having changed from negative to positive, the sheltering coefficient Γ = F1/F2 increased with increasing L/H. Γ decreased remarkably with steepening α and was independent of u. To fully incorporate the effects of the L/H and α , we propose a new sheltering function fitted with the experimental results:Γ =[1-1.56exp(sL/H)]*1.20α-0.08, s=0.001α-0.15. This function is compared with the previous sheltering functions and the actual ice conditions in the Arctic Ocean, pointing the way to obtain the final sheltering functions applicable to sea ice dynamics models.

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Sheltering of sea ice ridges in the ice–ocean drag force: implications from laboratory experiments

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Key points

- **The drag force on the downstream sea ice ridge is reduced significantly and even becomes negative due to the sheltering of the upstream ridge.**
- **The sheltering effect weakens with increasing dimensionless spacing, strengthens with increasing keel angle but isn't related to flow speed.**
- **A new sheltering function has been proposed, providing a reference for the parameterisation of ice-ocean drag coefficient.**

Abstract

The increasing movement and deformation of Arctic sea ice cover results in pronounced drag sheltering effects behind sea ice pressure ridges. This needs to be accounted for in the parameterisation of the form drag of ridges, thereby posing a challenge to evaluate the ice–ocean dynamic feedback. Laboratory experiments were conducted in a water tank to explore the sheltering effect between adjacent ridges of various geometries. The form drag forces on the keel models were measured, and the particle image velocimetry (PIV) system was employed to capture the flow fields surrounding the models to explain the variations in the drag force. The key sheltering parameters were the ratio between keel spacing and keel depth L/H, flow velocity u, and keel slope angle α. The results showed that the drag force F_1 on the upstream keel was close to the value of the single keel case, while the drag force F_2 on the downstream keel was lower, for $L/H \leq 10$ even opposite to the flow direction. Having changed from negative to positive, the sheltering coefficient $\Gamma = F_1/F_2$ increased with increasing L/H. Γ decreased remarkably with steepening α and was independent of u. To fully incorporate the effects of the L/H and α, we propose a new sheltering function fitted with the experimental results: $\Gamma = [1\text{-}1.56\exp(sL/H)]\times 1.20\alpha^{-0.08}$, $s = 0.001\alpha\text{-}0.15$. This function is compared with the previous sheltering functions and the actual ice conditions in the Arctic Ocean, pointing the way to obtain the final sheltering functions applicable to sea ice dynamics models.

Plain Language Summary

The wake generated by ridge keels in drifting sea ice causes critical sheltering on the downstream ice–ocean interaction, as the keels occupy a significant fraction of the under-ice mixed layer. The flow pattern in the under-ice boundary layer is difficult to measure in situ. Therefore, the sheltering effect was investigated in laboratory experiments, including drag force measurements and flow field mapping with particles. The results revealed that the sheltering effect is sensitive to the keel dimensionless spacing and slope angle but independent of the incoming flow speed. Based on finite depth experiments, a new sheltering function was fitted for the sheltering effect.

1 Introduction

The decline in Arctic sea ice thickness during recent decades has intensified sea ice movement (Kwok et al., 2018; Itkin et al., 2017; Stroeve et al., 2014), leading to the emergence of more deformed ice due to the low strength of thin ice (Itkin et al., 2017; Rampal et al., 2009; Albedyll et al., 2021; Herman, 2011; Leppäranta, 2011). It is anticipated to have a significant impact on sea ice feedback processes, such as ice drift patterns and momentum transfer (Castellani et al., 2014; Armitage et al., 2020; Boutin et al., 2019; Thielen K., 2021; Tschudi et al., 2020). The drag coefficients are critical parameters in these processes, and their modelling has evolved from semiempirical constants to parameterisation schemes associated with sea ice morphology (McPhee, 2008; Leppäranta and Omstedt, 1990; Lu et al., 2011; Brenner et al., 2021; Tsamados et al., 2014). The wind and ocean drag forces are partitioned for the skin friction drag, floe edge form drag, and ridge form drag (Arya, 1975; Garbrech et al., 2002), where the ridge term becomes more important with increasing proportion of deformed sea ice (Tsamados et al., 2014; Brenner et al., 2021; Castellani et al., 2018).

A remarkable sheltering effect exists between adjacent ridges due to the wake (Garbrech et al., 1999) that reduces the form drag of downstream ridges. To account for this effect, a sheltering function has been used in drag parameterisation (Lu et al., 2011; Lüpkes et al., 2012; Tasmados et al., 2014). Two forms of sheltering function, viz. exponential and power laws, have been applied: $\Gamma_1 = 1 - \exp(-0.18L/H)$ and $\Gamma_2 = [1-(L/H)^{-0.5}]^2$, where L is the keel spacing and H is the keel depth.

The exponential form was originally derived from experiments on terrestrial forests of varying density and spacing for the decay of downwind speed (Nägeli, 1964). Hanssen-Bauer and Gjessing (1988) applied this function for the first time to calculate drag attenuation in a field of ice floes. It was also utilised in the optimised drag parametrisation considering probability functions of a surface parameter developed by Mai et al. (1996). Lüpkes et al. (2012) adjusted the attenuation parameter from -0.18 to -0.5 based on tunnel observations by Lopez et al. (2005), and they further transformed this into a function of sea ice fraction by assuming a relationship between the spacing and sea ice fraction. However, this simplified scheme works less well at either high or low ice concentration.

Regarding the power law form, Tennekes and Lumley (1972) deduced that the maximum velocity loss behind a cylinder in a turbulent wake is a power function of the distance in a two-dimensional boundary-free plane shear flow. Based on this, Steele et al. (1989) provided a power-law decay function for sheltering between ice floes in a coupled sea ice-ocean model and analysed this sheltering with respect to floes size. Lu et al. (2011) then employed this function in the parameterisation of sea ice–ocean drag coefficient.

Tsamados et al. (2014) used the exponential sheltering function as they considered it to be simultaneously valid for the air-ice and ice-ocean interfaces rather than the power law. Brenner et al. (2021) compared the ice-ocean drag coefficient calculated from the force-balance using observational data with the parameterisation of Lu et al. (2011) and Tsamados et al. (2014). They showed that the difference of sheltering functions is an important factor affecting the prediction accuracy of the drag parameterisation, opening new ideas for improving the parameterisation schemes. Both exponential and power-law functions have been recognised and cited to date, providing valuable references for subsequent research. However, significant differences exist between land and oceanic boundary layers regarding highly permeable forest and variable sea ice structures (Hanssen-Bauer & Gjessing, 1988). The power function was derived for a cylinder in boundary-free plane flow, while sea ice drifts on the ocean surface, and its accuracy has not been verified by laboratory experiments or numerical simulations. Neither method considers the highly variable structural geometry of ridges. Thus, their applicability for sea ice is worth discussing. Although the wake for structures in tandem configuration has been widely studied in hydrodynamics (Kurtulmuş, 2022; Liu & Chen, 2002; Du et al., 2019; Luo et al., 1999; Rui et al., 2012; Pinarbasi et al., 2015; Kumar & Sen, 2021; Kim et al., 2008; Sohankar, 2012; Lin et al., 2002), no adequate wake functions exist to our knowledge since the studies have mainly focused on small spacings (Du et al., 2019).

It is quite laborious to conduct in situ measurements for the sheltering around ridges, especially due to the harsh conditions beneath sea ice, as opposed to the situation with the atmospheric boundary layer above ice surface (Prinsenberg & Peterson, 2002; Castellani et al., 2014; Garbrech et al., 1999). The depth of ridge keels is 4–5 times the sail height (Timco & Burden, 1997; Kharitonov & Borodkin, 2020; Strub-Klein & Sudom, 2012), and the keel depths are a fraction of 1/5 to 1/2 of the mixed layer depth while the corresponding fraction is usually less than 1/100 in the atmospheric boundary layer (McPhee, 2002). Therefore, the sheltering between keels deserves more attention. A combination of hydrodynamic laboratory experiments and numerical modelling seems to be the best way to address this issue. The former provides the physical truth of flow characteristics at ridges, and the latter extends the experimental results to real ocean conditions (Mortikov, 2016; Pite et al., 1995; Zu et al., 2021).

The goal of the present research was to investigate the sheltering effect between sea ice ridges through a series of water tank experiments, thus providing references for further numerical modelling and keel drag parameterisation schemes. This study is a follow-up to the water tank experiments of Zu et al. (2022) and Wang et al. (2022). Zu et al. (2022) examined the parameterization of the drag coefficient for a single ridge, while Wang et al. (2022) addressed the feasibility of an experimental system to study the sheltering between ridges using a fixed keel shape. Here this experimente has been improved from the preliminary tests and covered more comprehensive factors. This paper is organised as follows: the theory of parameterization on ice-ocean drag coefficient is briefly summarized in Section 2 as a background. And in Section 3, the experimental setup is introduced, including the force and flow field measurement system. The dependence of the drag force and sheltering effect on the flow velocity, dimensionless spacing, and keel slope angle are investigated in Section 4. Section 5 discusses the sheltering in finite water depth, the impact of sheltering function on ice-ocean drag coefficient and sea ice motion, and limitations in the laboratory experiment. Finally, conclusions are drawn in Section 6.

2 Theory of ice-ocean drag coefficient parameterization

Ice-ocean shear stress τ_{io} is commonly described by the quadratic drag law:

$$\tau_{\mathrm{io}} = \rho C_{io}(\boldsymbol{u}_{\mathrm{i}}-\boldsymbol{u}_{\mathrm{o}})|\,\boldsymbol{u}_{\mathrm{i}}-\boldsymbol{u}_{\mathrm{o}}\,| \tag{1}$$

where ρ is seawater density, C_{io} is the ice-ocean drag coefficient, $\boldsymbol{u}_{\mathrm{i}}$ is the drift velocity of ice and $\boldsymbol{u}_{\mathrm{o}}$ is ocean current velocity at the reference depth. Based on the drag partition theory, the total ice-ocean drag force is given as the sum of the form drags of the floe edge and ridge keel, and the skin friction drag (Arya, 1975). Accordingly, the total ice-ocean drag coefficient C_{io} in sea ice geometry-based parameterisation schemes can be calculated as follows (Lu et al.,2011; Tsamados et al., 2014):

$$C_{io} = C_r + C_f + C_s \tag{2}$$

$$C_r = \frac{1}{2} c_r A \frac{H}{L} \Gamma\left(\frac{L}{H}\right) P_{r0} \tag{2a}$$

$$C_f = \frac{1}{2} c_f A \frac{d}{L_f} \Gamma\left(\frac{d}{L_f}\right) P_{f0} \tag{2b}$$

$$C_s = c_s A\left(1 - m\frac{H}{L}\right), \frac{H}{L} \le \frac{1}{m} \tag{2c}$$

where C_r, C_f, and C_s represent ridge keel drag coefficient, floe edge drag coefficient, and skin drag coefficient, respectively, c_r , c_f and c_s are the corresponding local drag coefficients, A is the sea ice concentration, H is keel depth, L is keel spacing, and d/L_f is the ratio of the floe draft to floe length. The ratio H/L is the ridging intensity, and AH/L equals the sum of keel depths per unit length. In Eq. (2a, b) P_{r0} and P_{f0} are boundary layer integration functions, with some differences due to the choice of $\boldsymbol{u}_o$. Tsamados et al. (2014) set $\boldsymbol{u}_o$ equal to the velocity associated with the inner boundary layer which obeys the logarithmic distribution law, $P_{r0} = P_{f0} = [\ln(h_{ref}/z_0)/ \ln(z_{ref}/z_0)]^2$, where z_0 is the roughness length and the selection of h_{ref} and z_{ref} is referred to Tsamados et al. (2014). $P_{r0} = P_{f0} = 1$ when $\boldsymbol{u}_o$ was selected as the undisturbed far-field flow velocity by Lu et al. (2011). These two parameterisations of Eq. 2a using different boundary layer functions can be converted, with a transformation factor of 0.76 proposed by Zu et al. (2022). In Eq. (2c), m is skin drag attenuation parameter. In Eq. (2a, b), $\Gamma=\Gamma\,(L/H)$ is the empirical sheltering functions mentioned above. The same sheltering function is employed between adjacent ice floes (Eq. 2b) and between adjacent ice ridges (Eq. 2a). We only focus on the sheltering function in ridge keel drag in this study.

3 Methods

3.1 Experimental setup

The laboratory experiment was conducted in a water tank which was 11.5 m long, 0.45 m wide, and 0.50 m deep (Fig. 1a). The basic experimental setup was originated by Wang et al. (2022) but has been improved here as summarized below. Similarity treatment was adopted for the major parameters based on dimensional analysis. The dependent quantities were the drag force F, keel spacing L, keel depth H, water depth D, flow velocity u, keel slope angle α, fluid density ρ, and kinematic viscosity coefficient of fluid v. H, ρ, and u were selected as the fundamental dimensional quantities, and the derived dimensionless quantities were (Table 1): $\pi_1 = c_r$ is the local drag coefficient, π_2 is the dimensionless spacing, π_3 is Reynolds number (Re), and π_4 is dimensionless depth. It is necessary to ensure that the ranges of these dimensionless quantities in the water tank experiment are consistent with the natural conditions.

Table 1 Similarity basis of the model experiment

Dimensionless quantities	π_1	π_2	π_3	π_4	π_5
Expression	$\frac{F}{\rho u^2 H}$	$\frac{L}{H}$	$\frac{uH}{\nu}$	$\frac{D}{H}$	α

The keel model was set up as a solid isosceles triangle, which has been used in many laboratory experiments (e.g., Pite et al., 1995; Zu et al., 2021) and geophysical applications (Roberts et al., 2019; Lemieux et al., 2015). The model material was plexiglass, as used by Waters and Bruno (1995), Pite et al. (1995), and Zu et al. (2021). The model shape corresponds to observed sea ice ridge keels (Timco & Burden, 1997), but the macroporosity of 11-20% between keel blocks (Kharitonov & Borodkin, 2020; Strub-Klein & Sudom, 2012) was ignored. A low macroporosity may occur in nature near the waterline due to ridge consolidation (Leppäranta et al., 1995; Roberts et al., 2019). The keel slope angle of first-year ice is mostly in the range of 20°-50°, with a mean value of 29.6° (Strub-Klein & Sudom, 2012; Timco & Burden, 1997; Davis &

Wadhams, 1995) and a maximum of 87° (Kharitonov & Borodkin, 2020). The keel depth (minus background ice thickness) mostly varies from 2 to 12 m, with an average of 5 m and maximum exceeding 27 m, (Metzger et al., 2021, Kharitonov & Borodkin, 2020; Wadhams et al., 2011).

The parameter settings for the experiment are given in Table 2. All four keel depths H were measured with the fixed tank depth D = 0.45 m, thus D/H = 3.75–22.5, whereas the variable water depth experiments were conducted with α = 45°, H = 0.12 m, and D = 0.30 - 0.50 m. For the keel model H = 0.02 m, the lowest flow velocity is u = 0.2 m/s since the drag force is too small (down to 10^{-2} N) to be accurate for u = 0.1 m/s. The model for α = 90° was a 5 mm thick rectangular slice.

The dimensionless spacing L/H is a classical parameter in wake analysis (Du et al., 2019), and it is equal to the inverse ridging intensity, which is a common spatial statistic of ridging (see Leppäranta, 2011). It was ensured that the keel models of different depths corresponded to fixed L/H. The min and max L/H achievable for different keel sizes depend on the width of the model and the length of the tank: $L_{\min} = 2(H+0.02)/\tan(\alpha)$, where 0.02 m was freeboard, and $L_{\max}$ = 6 m in the stable uniform flow section, accounting for the length of the tank and the locations of the inlet and outlet. The characteristic length in the Reynolds number was chosen as the wetted perimeter length of the keel model, $Re = [2uH/\sin(\alpha)]/\upsilon$, $\upsilon = 1.003\times10^{-6}$ m^2/s. The range of Re was 8×10^3 to 2.47×10^5. The laboratory experiments were considered similar to the natural marine environment when the flow was turbulent or $R\text{e} > 10^4$ (Zu et al., 2021). The cases of $R\text{e} < 10^4$ were at the margin and may occur in nature at near stationary ice conditions.

Table 2 Experimental cases for the drag force measurement. The asterisk shows the cases the flow field was measured by the PIV system.

Drag force measurement	
u (m/s)	0.1, 0.2,0.25*,0.3*,0.35
H (m)	0.02*,0.04*,0.08*,0.12*
α (°)	20*,30,45*,60*,90
L/H ^{Note1}	2.5*, 5*, 7.5*, 10*, 20*, 30, 50,70,100
D (m) ^{Note2}	0.50,0.45*,0.40,0.35,0.30

3.2 Drag force measurements

The drag force measurement device is shown in Fig. 1b. The selected speed was obtained by adjusting the frequency of the flow generator machine, which is linearly related to the speed. A flow stabiliser was added to the inlet of the tank to ensure a uniform inflow. Three brackets were placed on the side rails of the tank, and they were used to connect the acoustic Doppler velocimeter (ADV), the upstream and downstream keel models, abbreviated as keel-1 and keel-2, respectively.

Real-time monitoring and recording of the incoming flow velocity was conducted using the ADV. The force sensors were fixed to the keel models vertically and connected to the screw on the bracket integrally, enabling height adjustment. Two-component force sensors were chosen to measure the form drag force in the flow direction, with a range of 10 N. To reduce errors in the data, the spacing of the keels was adjusted by only moving keel-2. In addition, a round rod (6 mm diameter) was fixed to keel-1 bracket as a nonload item (Fig. 1b). Its original goal was to record the vibration of the flow generator and the brackets above the tank that helped to remove the disturbances on the measurements of keel drag force. This was similar with the experiments used to record the noise of cylinders with a large aspect ratio in a wind field (Reza et al., 2023). We verified that the effect of disturbances such as flow generators was extremely small (<0.9%) and could be ignored. Altogether, 730 groups of force measurement data were obtained (Table 2).

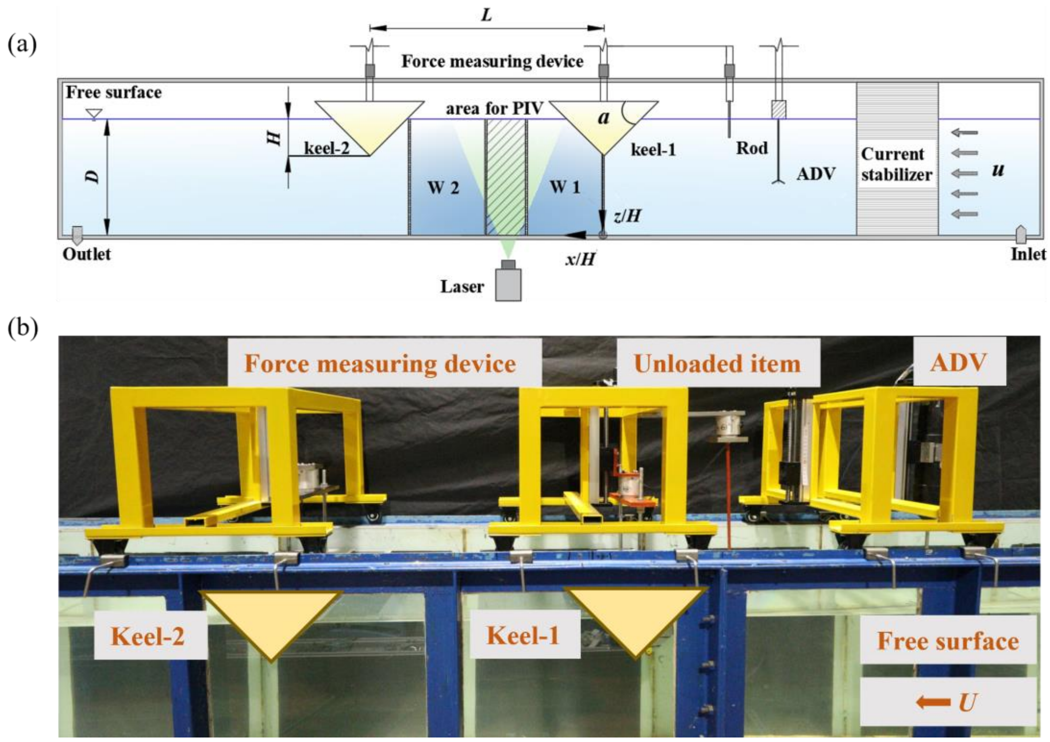

Fig. 1 (a) A schematic drawing of the study tank. W1 and W2 represent the windows of the PIV shots, and the shaded area in the middle is the overlap. (b) A photograph showing the model test device.

3.3 Flow field measurement

Particle image velocimetry (PIV) is an instantaneous, multipoint, noncontact hydrodynamic measurement method that can record velocity distributions over many spatial points in the same transect, providing a rich spatial structure of the flow field (Westerweel et al., 2013). The PIV system was used in some groups in the experiments (Table 2) with the shooting positions (windows 1 and 2) shown in Fig. 1(a). The origin of the coordinate system was located at the intersection of the midline of keel-1 and the free surface, and the positive axis directions are shown by the arrows in the fig.1(a).

The PIV installation diagram is depicted in Fig. 2(a). The steps of the PIV method were as follows: First, to eliminate the excess light in the environment, darkroom conditions were created, and the test area was shielded. The tracer particles added to the fluid were hollow glass beads with a diameter of 50 μm and a density of 1.05 g/cm^3, and with excellent light reflectivity and high followability. A continuous laser with a wavelength of 532 nm was used as the light source to illuminate the area of interest. A black coating was added to the model to reduce its surface reflection and the edge effect. Finally, the Photron FastCAM SA5 ultrahigh-speed camera was used to take continuous images at a fixed position in the given time interval, with a resolution of 1024 × 1024 pixels (Fig. 2b). It can be adjusted in both the horizontal and vertical directions, ensuring that the camera is perpendicular to the laser surface when capturing.

The Window 1 and Window 2 were both of approximately 45 × 45 cm size. The overlapping areas of the windows were averaged and then spliced together. The captured frame rate was 250FPS and the storage time for the cases was 60s. An interrogation window of 32 × 32 pixels was used to capture a sort of high displacement, and then 16 × 16 pixels were taken in the final pass to give a refined vector resolution (Xue et al., 2023). The maximum pixel displacement in the PIV image was 5.47 pixels at u= 0.25 m/s. Considering the systematic error of 2D PIV, the window deformation, and the error from speed control, the relative uncertainty was 4-5% (Singha et al., 2009; Jin et al., 2014), equivalent to 0.22-0.27 pixels.

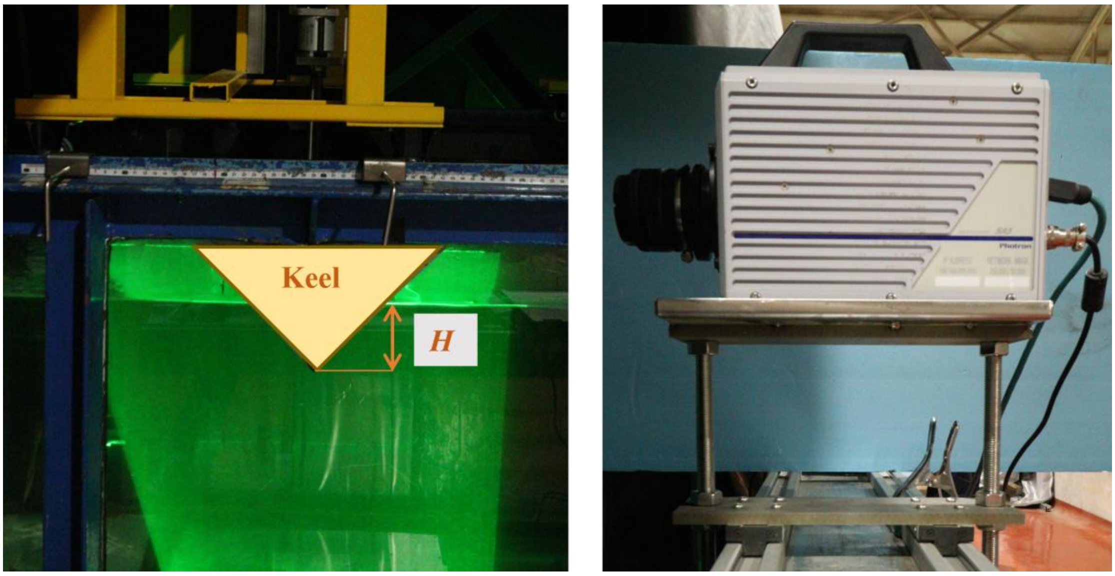

Fig. 2 (a) PIV experimental installation diagram; (b) Camera arrangement diagram

4 Results

4.1 Drag force on ice ridges

Fig. 3 shows the drag forces on the upstream and downstream keels vs. L/H for α

= 45° and H = 0.08 m. The other cases are not shown because of the similar patterns. Fig. 3(a) shows that L/H influences F_1 only within L/H <10, where F_1 increased by 5% due to the presence of keel-2. Thus, the upstream keel drag is the same as in the case of an individual keel which has been investigated thoroughly by Wu (2016) and provides a reference for the decay of the downstream drag F_2. Fig. 3(b) reveals that F_2 was reduced as a result of sheltering by the upstream keel, and this attenuation decreased with increasing L/H as F_2 gradually approached F_1 as described in more detail in Section 3.4.

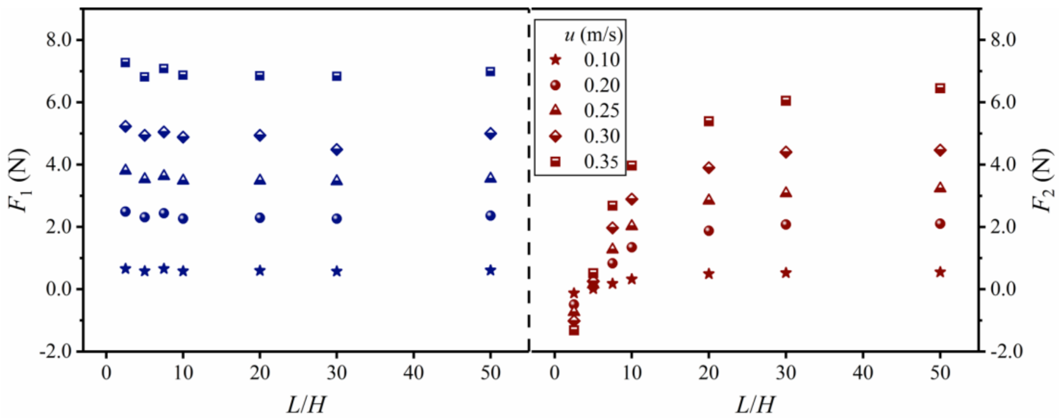

Fig. 3 (a) The drag force F_1 and (b) the drag force F_2 vs. the L/H for α = 45° and H = 0.08 m.

The drag force $F_2 = F_2(u^2)$ for α = 45° and H = 0.08 m is shown in Fig. 4. The dependence was linear, consistent with the classical drag force formula (Tennekes &

Lumley, 1972; Arya, 1975; Wamser & Martinson, 1993). F_2 appeared negative at $L/H \leq 5$, when keel-2 was located in the recirculation zone formed by flow separation behind keel-1. This reverse drag force was also linear with u^2. The presence of different ranges of recirculation zones has been demonstrated in submerged wake experiments for a conical island (Oruo et al., 2017) and in tank experiments with rectangular columns placed in series (Pinarbasi et al., 2015).

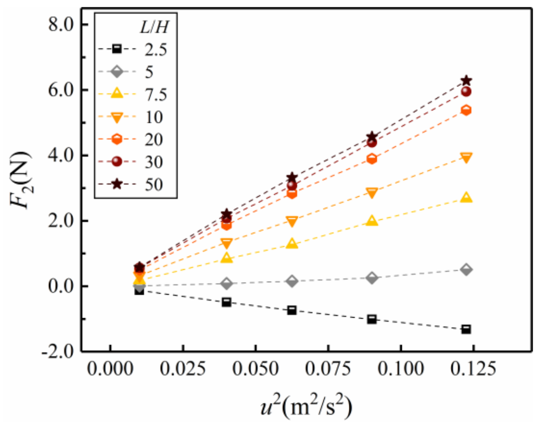

Fig. 4 The drag forces F_2 vs. the velocity squared u^2 when α = 45° and H = 0.08 m

In the mechanism of drag variation, the main turbulent structures and the development in the wake field around keels are essential. The time-averaged streamlines and dimensionless velocity $\overline{u}/u_0$ for α = 45°, u_0 = 0.25 m/s, and L/H = 5 (H = 0.08 m) are plotted in Fig. S1, corresponding to F_1 = 1.94 N and F_2 = -0.06 N. The characteristic structures in the wake mainly included recirculation zones, vortex shedding, separated shear layers and an acceleration zone (Ouro et al., 2017), analysed in Text S1. The development of turbulent structure leads to changes in the pressure difference between the leading and lee edges of the keel-2, which is the essence of the drag force.

4.2 Influence of flow velocity on the sheltering effect

The ratio of the drag forces $\Gamma = F_2/F_1$ is defined as the sheltering coefficient, which characterises the strength of the sheltering between the keels. Fig. 5 shows this coefficient as a function of the squared flow velocity for $\alpha = 45°$ and $H = 0.12$ m. As u^2 increased, Γ remained stable within 4.2%. According to the dimensional analysis in Table 1, the flow velocity u impacted the sheltering effect by changing only Re, which is crucial in the laminar flow regime but barely affects the turbulent regime (Zu et al., 2021). Since the ocean currents under sea ice are mostly turbulent (McPhee, 2008; Kharitonov & Borodkin, 2020), Γ is independent of the u. Based on the quadratic drag laws, $\Gamma = F_2/F_1 \sim u_2^2/u_1^2 =$ constant at a fixed L/H, where u_1 and u_2 are the flow velocities at keel-1 and keel-2, respectively. Thus, u_2/u_1 depends only on L/H for the fixed $\alpha = 45°$, implying that the velocity deficit caused by keel was not connected with the incoming flow. Li and Sherman (2015), in a study focused on the aerodynamics and morphodynamics of the sheltering effect behind also confirmed that the ratio of the disturbed velocity to the incoming velocity at a certain elevation and distance was nearly an independent factor.

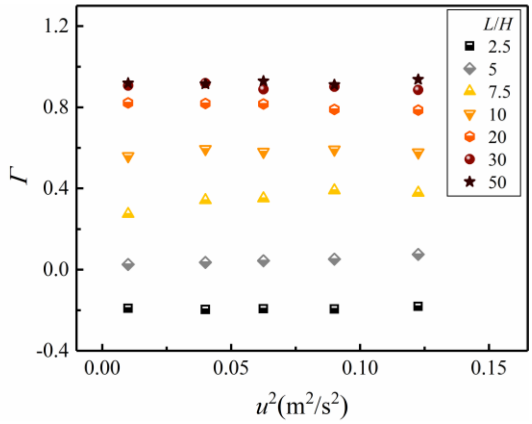

Fig. 5 The sheltering coefficient Γ vs. the squared velocity u^2 for α = 45° and H = 0.12 m

4.3 Influence of the ridge spacing on the sheltering effect

Γ as a function of the L/H for α = 45° is shown in Fig. 6. The error bars show the standard deviation of different sizes of keels. An exponential function was chosen to fit in the data (R^2 =0.99), whose form was similar with the sheltering function of Hanssen-Bauer and Gjessing (1988). Based on the growth and asymptotic behaviour, the function was divided into two parts in the analysis, for L/H <30 and $L/H \geq 30$.

At L/H < 30, keel-2 drag was subject to strong attenuation from the wake of keel-

1. The sheltering coefficient was negative and changed sign at approximately L/H = 5, a similar critical value of L/d=5 was found for the drag on the downstream cylinder (diameter d) in simulations with two cylinders in tandem by Li et al. (2018). An examination of the flow pattern was needed to interpret the phenomenon. For L/H > 5, sheltering gradually became weaker.

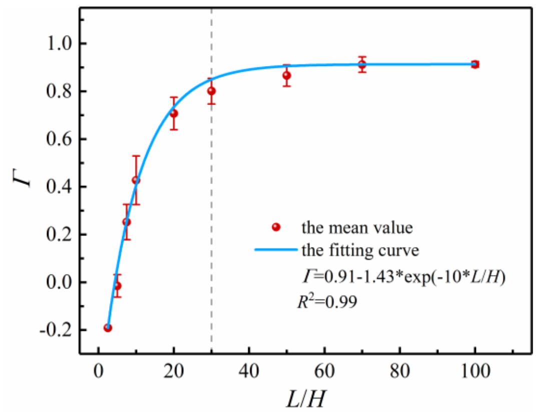

Fig. 6 The sheltering coefficient Γ vs. dimensionless spacing L/H when α = 45°. The blue curve represents the fit for $\Gamma = \Gamma(L/H)$. The dashed line at L/H=30 separated the growth and asymptotic parts of the curve.

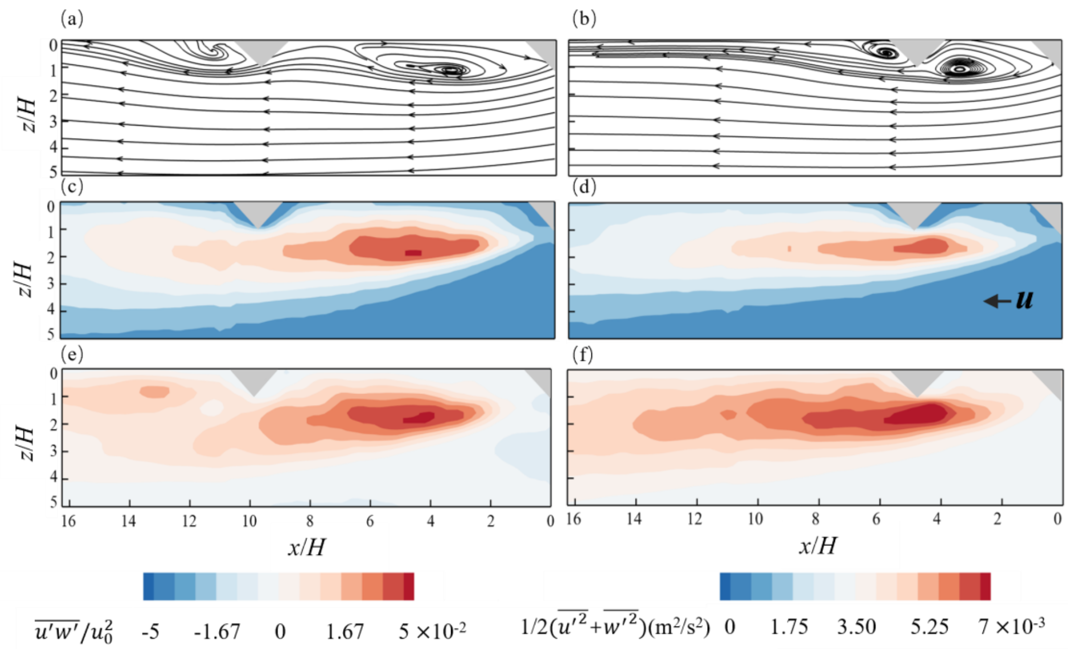

Fig. 7. Contours of time-average streamlines (a, b), turbulent kinetic energy $1/2(\overline{u'^2}+\overline{w'^2})$ (c, d), and dimensionless Reynolds shear stress ($\overline{u'w'}/u_0^2$) (e, f). *L*/*H*=5 (b, d, f) and *L*/*H*=10 (*H*=0.04 m) (a, c, e). α = 45°, u_0=0.25 m/s, and u' and $w'$are the velocity fluctuations along the flow and vertical directions, respectively.

Fig. 7 shows the streamlines, turbulent kinetic energy (TKE), and dimensionless Reynolds shear stress for *L*/*H*=5 and *L*/*H*=10, α = 45°, corresponding to Γ = -0.07 and 0.34, respectively. Reducing the spacing between the keels led to an increased local blockage that induced more complex flow patterns. As *L*/*H* increases, the mixing wake around the keels will exhibit three major regimes (Kurtulmuş, 2022; Sakamoto et al., 1987; Sohankar, 2012). Two are shown here, with differences in the dominant turbulence structure and development mechanism of the wake as the fundamental reason for the drag variation.

When the two keels are very close (Fig. 7b, d, f), the shear layer separated by keel-1 will adhere to the surface of keel-2 where the vortex wraps around, so they can be treated as one bluff body (Du et al., 2019). This flow pattern is denoted as a single slender-body regime (Sohankar, 2012), which exposed the leading face of keel-2 to a strong suction and resulted in a thrust (negative F_2) rather than a drag force with $\Gamma < 0$ for L/H=5. The peak values of TKE and Reynolds stress occurred underneath keel-2 along the transition from the recirculation region to the far wake, corresponding to the region where shear-layer vortices lost coherence due to interactions with the incoming flow and backflow. The continuous vortex structure was gradually shed. The Reynolds stress was consistently higher up to x/H=14, which meant a long section of intensive turbulent momentum exchange. Thereafter, the stress gradually dissipated downwards in the direction of the flow.

Figs. 7a, c, e show the reattached flow regime (Sohankar, 2012), characterised by synchronised vortex shedding from each cylinder. The separated shear layer at keel-1 found sufficient space to develop and roll into the distance between two keels, with the reattachment positioned in front of keel-2 (x/H = 6-8). Hence, secondary separation occurred at the tip of keel-2 which presents a co-shedding vortex flow regime (Kurtulmuş, 2022; Sohankar, 2012). The vortex length became distant with the first flow separation reattaching at *x/H* = 7, while the second reattachment point was shifted to *x/H* = 14. The locations of the peak values of TKE and Reynolds stress were advanced to *x/H* = 2-4 between keels, accompanied by the enhancement of the TKE and the weakening of the Reynolds stress which was elevated at the intersection of eddies and incoming flows behind keel-2 due to the induced secondary separation, but it was weaker. The reduction in the turbulence intensity in the wake also indicated a decrease in the sheltering capacity of the wake.

In the range of $L/H \geq 30$, Γ increased with L/H towards the asymptote, and the wake field was gradually restored to an undisturbed state. The third mode, appearing in this far-wake region, manifested as vortices falling off independently of the two structures. In the aerodynamic experiments by Sakamoto et al. (1987) on two square prisms in tandem, this wake mode occurred when $L/H > 27$.

4.4 Influence of the keel slope angle on the sheltering effect

Fig. 8 shows Γ against α, with the error bars representing the standard deviation. Since negative values of Γ occurred, the logarithmic coordinate transformation was performed for Γ+0.5. With increasing slope, the sheltering coefficient tended to decrease. Linear fits in the plot were excellent (R^2=0.98), implying a power function relationship $\Gamma+0.5 = 3.02*\alpha^{-0.31}$ ($20° \leq \alpha \leq 90°$). The decline in Γ was strong at α = 20°–30°, which is the common range of the slope Arctic sea-ice ridges (Timco & Burden, 1997; Strub-Klein & Sudom, 2012). Furthermore, the decrease of Γ caused by the increasing α revealed different characteristics in the regimes L/H < 20 and L/H ≥ 20, represented in red and blue colours, respectively. The wake can be divided into near and far wake zones (Vermeer et al., 2003; Williamson, 1996), and the influence of the keel shape on the wake field was mainly concentrated in the near-wake region, while the geometry was no longer important in the far-wake region. For instance, when α increased from 20° to 90°, Γ decreased from 0.65 to 0.22 at L/H = 10 and from 0.93 to 0.78 at L/H = 50.

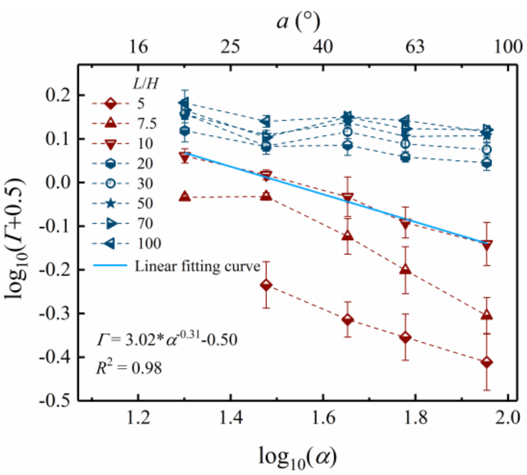

Fig. 8 The sheltering coefficient Γ vs. slope angle α. The dashed red curves represent

the near-wake region, the dashed dark blue curves represent the far-wake region, and the solid blue line represents the fitted curve for L/H =10.

More insight into the flow characteristics in the near-wake region could be obtained by extracting the PIV flow field results at different slopes. Fig. 9 illustrates the time-average streamlines, TKE, and Reynolds shear stress for α = 20° and α = 60° when L/H=10, corresponding to Γ = 0.65 and 0.31. The result can be analysed in conjunction with the flow field at α = 45° and L/H=10 in Fig. 7(a, c, e). The wake flow extent at α = 20° had a small longitudinal range of z/H = 1-1.5, and the secondary separation was weak near keel-2, with no significant vortex production behind (Fig. 9a). The attachment point was at x/H = 5-6. The flow separation at keel-1 with α = 60° was more intense (Fig. 9b), and the reattachment point was shifted to x/H = 7-8, implying a deferred shedding process of the vortex. Steeper angles lead to increased pressure gradients around the keel, which affect the flow separation process and the vortices that roll up behind the keel, resulting in different sized vortex structures, vortex shedding patterns, and dissipation (Wang et al., 2017).

Overall, the wake generated with α = 60° produced stronger turbulence intensity and more active flow separation processes compared to α = 20° and α = 45°, leading to an increase in sheltering strength and extent. The larger range of TKE and Reynolds stress peak values was maintained up to *x/H* = 7-8 and *z/H* = 3-4. The increase in the Reynolds stress enhanced the momentum transfer across the shear layer, thereby delaying wake recovery. The first triggered peak value occurred at *x/H* = 2-4, developing and dissipating along the flow direction. The Reynolds stress peaked again but at a significantly lower level than in the first one due to the secondary disturbance of keel-2 that was also related to α. The Reynolds stresses behind keel-2 were higher with α = 60° than with 45° and 20° due to the larger velocity gradient of the fluid flowing through the keel. The greater shear stress intensifies the level of turbulence in the wake, accompanied by a significant increase in TKE.

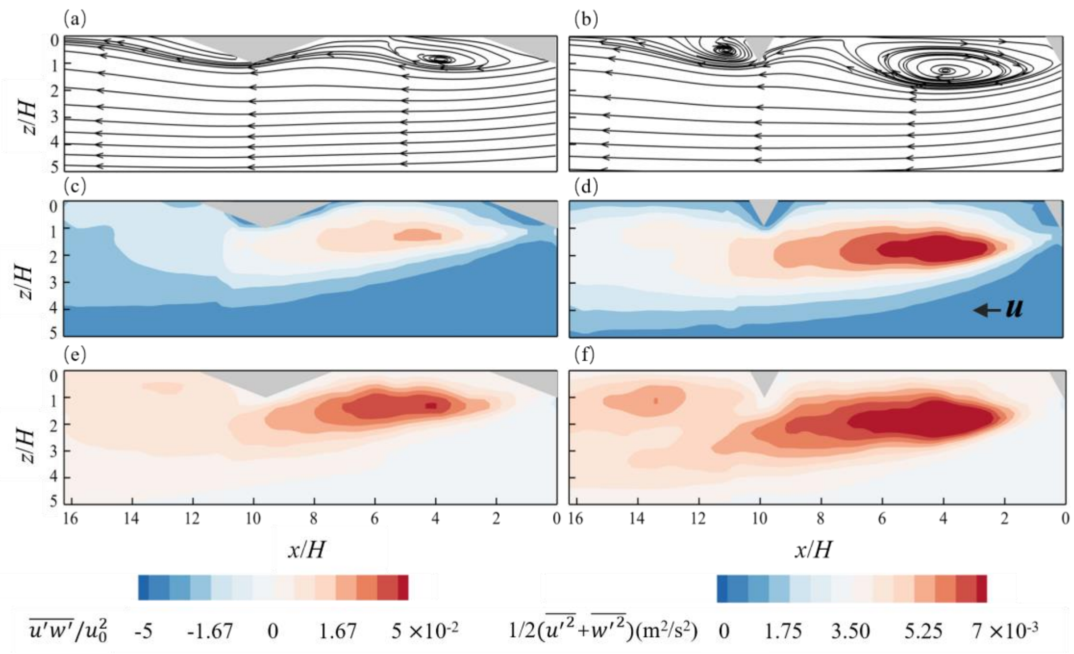

Fig. 9 Contours of time-average streamline (a, b), turbulent kinetic energy $1/2\left(\overline{u'^2}+\overline{w'^2}\right)$ (c, d), and Reynolds shear stress $\overline{u'w'}/u_0^2$ (e, f) for α = 20° (a, c, e) and α = 60° (b, d, f) when L/H = 10, corresponding to Γ = 0.65 and 0.31, respectively.

5 Discussion

5.1 Sheltering functions

The sheltering function was affected not only by the dimensionless spacing L/H but also by the slope angle α, but it was independent of the flow velocity u. In Sections 4.2-4.4, the curve $\Gamma = \Gamma(L/H)$ at α=45° was better fitted by the exponential function (Fig. 6), similar with the previously presented sheltering function. The relationship between Γ and α was given by a power law (Fig. 8). To obtain a new expression of the sheltering function based on the present experimental data, the two functional forms above are combined. The least squares method was used for the optimal solutions of the pending parameters. The resulting sheltering function $\Gamma = \Gamma(L/H, \alpha)$ is:

$$\Gamma = [1\text{-}1.56\exp(sL/H)]\times 1.2\alpha^{-0.08}\ ,\quad s = 0.001\alpha\text{-}0.15 \tag{3}$$

The range of application is $2 \leq L/H \leq 110$ and $10° \leq \alpha \leq 90°$. Formerly s was a constant s = -0.18 (Hanssen-Bauer & Gjessing, 1988) and s = -0.5 (Lüpkes et al., 2012), but here it was found that s increased with α. To account for this, s was taken as a linear function of α. The exponential factor reflects the influence of both arguments, while the power function factor depends only on the slope angle. First, the exponent sL/H determines the sign of the sheltering coefficient. At sL/H = -0.44, we have $\Gamma = 0$ and s = -0.14 when α =10° and -0.06 when α =90°. The minimum and maximum values of sL/H were -16.8 and -0.12, respectively; Γ >0 when -16.8< sL/H < -0.44, while Γ <0 when -0.44< sL/H < -0.12. In the limiting cases, when $L \rightarrow 0$, $\Gamma \rightarrow -0.672\alpha^{-0.08}$, and when $L \rightarrow$ infinity, $\Gamma \rightarrow 1.20\alpha^{-0.08}$. Ninety percent of the increase in Γ with increasing L was concentrated at $L/H \leq 30$. In this range, the reduction in Γ could reach 69% due to the steepening of the keel slope. Fig. 10 shows the fitted curves (Eq. 3) for α =20°, 45° and 60° within $2 \leq L/H \leq 110$, with R^2 = 0.97, RMSE =0.07.

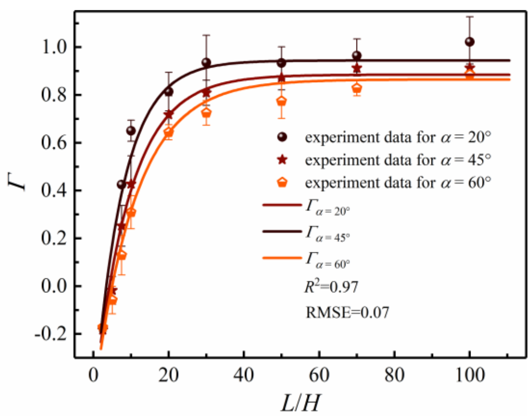

Fig. 10 Comparison of Eq. (3) with the experimental data. The adjusted R^2 is 0.97, and the root mean square error is 0.0697. The solid points are the experimental results, and the error bars represent the standard deviations.

Fig. 11 compares our formula (Eq. 3) with the two previously reported equations. The pink shaded area presents Eq. (3), extended through α = 10°-90°. The average slope angles in different papers varies, but they are generally about 30° which was chosen here as the representative angle (Timco & Burden, 1997; Strub-Klein & Sudom, 2012). Eq. (3) was then $\Gamma_{30} = 0.92\text{-}1.44\exp(-0.12L/H)$. The factor -0.12 in the exponent is larger than the fixed constant -0.18 (Hanssen-Bauer & Gjessing, 1988) and -0.5 (Lüpkes et al., 2012). The minimum value of this factor in Eq. (3) was -0.14, and thus Eq. (3) represents stronger sheltering than the exponential function Γ_1 but weaker than the power function in Γ_2. Compared to Γ_{30}, the exponential function was 15.2% higher, while the power function was 17.1% lower within L/H=2.5-100. Eq. (3) includes the reverse drag force at small spacings and the effect of the keel slope.

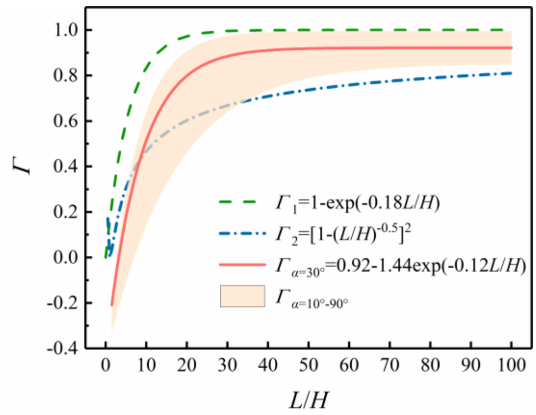

Fig. 11 Comparison between Eq. (3) (the pink shaded for α = 10° - 90°) and the previously reported exponential (green dashes) and power (blue dotted lines) functions. α = 30° represents the typical slope angle of keels.

The sheltering coefficient in Eq. (3) can reach down to -0.44, while in the other two functions, the minimum values were 0.30 and 0.08 when L/H = 2. Such small spacings are uncommon in a real sea ice cover, but ridges sometimes form in closely packed clusters. Valenti et al. (2021) proposed from observations that L follows the lognormal distribution presented by Wadhams and Davy (1986), with the third quartile values Q3 = 292 m and 277 m in the Beaufort and Chukchi Seas, respectively, and the average keel depth is approximately 5-8.5 m. As a result, L/H was mostly in the range of less than 60, accompanied by Γ from -0.14 to 0.93 for α =30° (Eq. 3). Thus, the form drag from ice ridges was significantly weakened due to the sheltering.

This effect will be strengthened as the frequency of ice ridges increases during the winter (Steele et al., 1989). Besides, the occurrence of ridge keels tends to be consecutive and overlapping in the spatial underice profiles from the moored IPS and ADCP data of Valenti et al. (2021), resulting in the sheltering of the wake being superimposed and enhanced.

The inclination angle of obstacles has been validated in hydrodynamics and sea ice dynamics as a key parameter of the drag force of two square pillars (Du et al., 2019; Yen et al., 2008) and ridge keels (Zu et al., 2021). In particular, the geometry of ridged ice varies greatly for the depth and cross-sectional shape, e.g., a maximum depth of 27 m and a maximum slope angle of 87.5° were observed by Kharitonov & Borodkin (2020). The differences in α depend on many factors, such as wind speed and current direction, which drive sea ice deformation. Observations show keel slopes in the Barents Sea of 8°-29° and in the Shokalsky Strait of 11.2°-87.5° (Sand et al., 2015; Kharitonov & Borodkin, 2020). Neglecting the changes in the slope angle, i.e., with the fixed angle of 30° in Eq. (3), the form drag on ice ridges in the Barents Sea will be underestimated by 17.7% within L/H = 10-40, while it may be overestimated by as much as 43.5% in the Shokalsky Strait.

5.2 Views on sea ice dynamics

The most significant advance between the new sheltering function Γ and the previous versions Γ_1 and Γ_2 is the includes of the keel angle, inevitably inducing a change in C_{io} in Eq. (2), which further changes the contribution of oceanic drag force τ_{io} in the sea ice momentum equation. In the free-drifting conditions, sea ice motion depends mainly on the wind and current drag forces, providing a good scenario to check the impact of the new sheltering function. Fig 12. shows the variation of C_{io} (a-c), wind factor (the ratio of sea ice drift velocity to wind velocity) $|u_i|/|u_a|$ (d-f) and the deflection angle θ (g-i) calculated using three different sheltering functions (a, d, g: Γ_1; b, e, h : Γ_2 ; c, f, i: Γ in Eq.(3)) with keel geometric parameters H/L and α when A = 0.8. The drag coefficients are calculated using Eq. (2) with reference to the parametrisation scheme of Lu et al. (2011), and the calculation of the wind factor and deflection angle follows the momentum equation of free-drifting sea ice by Leppäranta (2011), with the formulas and parameter values shown in Text S2. Combining data from Valenti et al. (2021) on the distribution of H and L, and observations of H/L from Berner et al. (2021), it can be found that most cases fell within $H/L \geq 0.01$. However, earlier observations show that is predominantly in the range of 0.001-0.01 (Davis & Wadhams, 1995; Granberg & Leppäranta, 1999). As a result, the range of H/L is set to 0.001 to 0.1, covering most keels.

Based on Fig. 12(a-c), C_{io} increases as H/L increase but the impact of α is not obvious when $0.001 \leq H/L \leq 0.01$. Differences between the three schemes are clearly visible when $H/L \geq 0.01$. C_{io} is higher with Γ_1 and lower with Γ_2, and in between with Γ. Γ affects C_{io} by changing the contribution of C_r in Eq.(2a). When $H/L \geq 0.01$, C_{io} using Γ varies nonlinearly with the coupling of H/L and α in Fig. 12c, instead of monotonically decreasing as in Fig. 12a and b. L/H and α actions on the wake structure have been illustrated in the PIV results above. The max C_{io} in Fig. 12c only appeared in the region of $0.05 \leq H/L \leq 0.1$ and α=10°-30°.

$|u_i|/ |u_a|$ is a key indicator of wind stress transfer, determining sea ice drift. Based on the general solution of the free drift equation, $|u_i|/ |u_a|$ is a function of Nansen number (Na) and Rossby number (R) where $Na \propto (C_{ai}/C_{io})^{0.5}$ and $R \propto (C_{ai}C_{io})^{-0.5}$. For $|R|<0.2$, $|u_i|/ |u_a| \approx Na \propto (C_{ai}/C_{io})^{0.5}$ (Leppäranta. 2011). So, $|u_i|/ |u_a|$ is in positive correlation with Γ^{-1}. $|u_i|/ |u_a|$ are mostly in 0.012-0.024, consistent with the observation of Cole et al. (2017) in the Canada Basin. When $H/L \geq 0.01$, $|u_i|/ |u_a|$ also varies nonlinearly due to the sheltering effect. Interestingly, in the range of $0.06 \leq H/L \leq 0.1$, u_i / u_a reaches its maximum 0.024 when α varied from 10 to 90°, implying the amplification of stress transfer from the atmosphere.

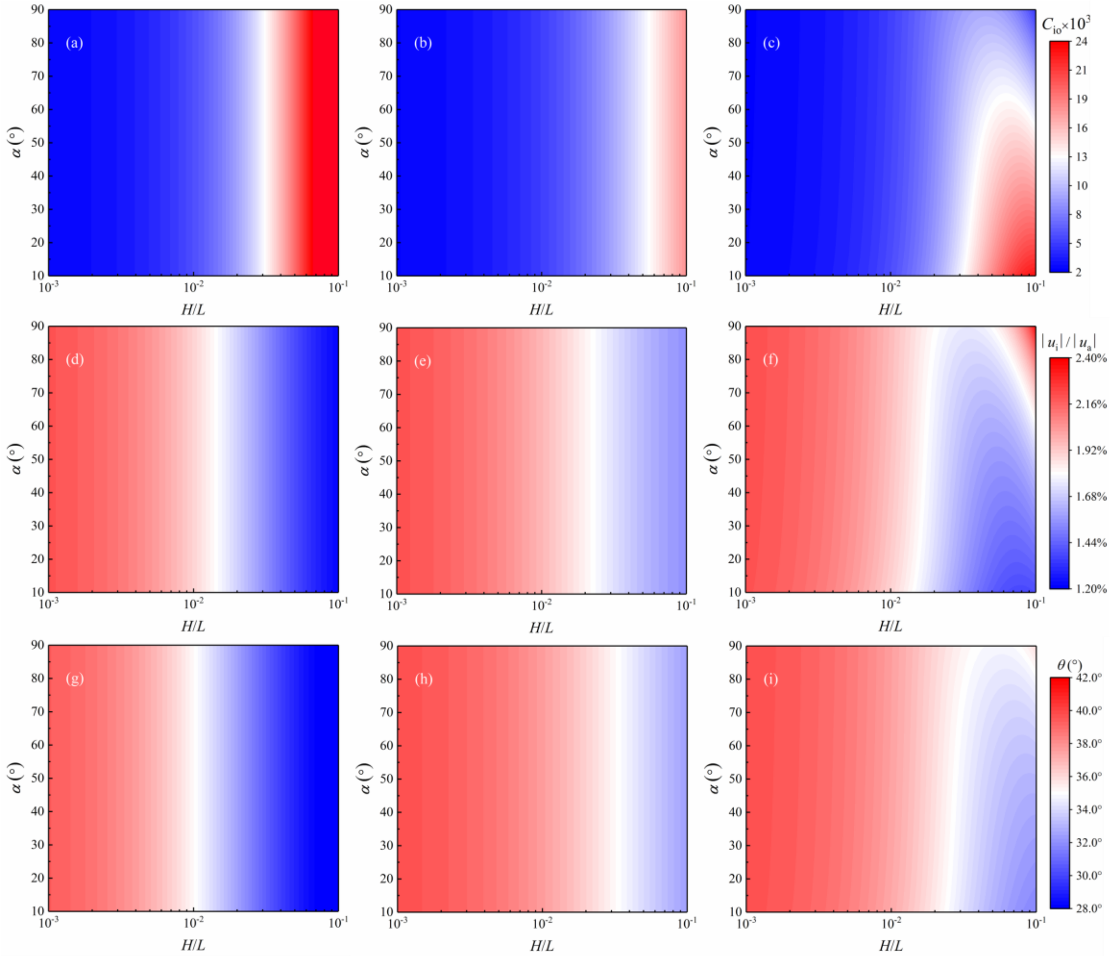

Fig.12 Variation of C_{io}, $|u_i|/|u_a|$ and θ with keel geometric parameters H/L and α when $A = 0.8$: (a, d, g) sheltering function is Γ_1; (b, e, h) Γ_2; (c, f, i) Γ. The drag coefficients are calculated with reference to the parameterization of Lu et al. (2011) and the calculation of $|u_i|/|u_a|$ and θ follows the momentum equation of free-drifting sea ice by Leppäranta (2011), with the formulas and parameter values shown in Text S2.

In the case of $|u_i|/|u_a| \rightarrow Na$, θ can be simplified to a function of R when the surface wind angle and oceanic Ekman angle are given (Leppäranta. 2011). Therefore,

θ is a function of $(C_{ai}C_{io})^{-0.5}$, then θ is positively correlated with Γ^{-1}. The variation pattern of θ is independent of the chosen values of wind angle and oceanic Ekman angle for $|R|<0.2$, as shown in Text S2. θ presented in Fig13. i is higher than that in Fig12. g while lower than Fig12. h. With the increasing of H/L from 0.01 to 0.1, θ decreases about 36% when α =30°. With the increasing of α from 10 to 90° when H/L=0.05, θ increases about 24%.

5.3 Laboratory experiments vs. polar oceans - limitations and uncertainties

This paper has been devoted to laboratory experiments on the sheltering effect between ice ridges and a new sheltering function has been proposed. The experimental results provide solid references for parametrisation in sea ice dynamics, but differences in the boundary conditions between the water tank and the Arctic Ocean must be clarified because they partly limit the direct application to polar oceans.

Firstly, the upper boundary in the tank was a free surface, while the polar ocean surface is covered with ice. This mainly affects whether the incoming reference velocity is chosen to be a logarithmically-law distributed flow velocity in the inner boundary layer Lüpkes et al., 2012) or the far-field velocity independent of the thickness of the boundary layer (Shaw et al., 2008; Österlund et al., 2000). The inner logarithmic layer is approximately 2 m deep in winter（Kharitonov & Borodkin, 2020）and less in summer (Cole et al., 2017; Gallaher et al., 2016), as estimated by an empirical formula related to the Ekman depth (Shaw et al., 2008). Therefore, the logarithmic layer is of concern primarily for small ice ridges in winter.

The conversion factors of the two reference velocities for the single keel form drag were derived by Zu et al. (2021) as 1.1-1.3, decreasing with increasing ridge height. However, we are concerned with the effect of the reference velocity on sheltering characterised by F_1/F_2. Section 4.2 showed that the wake generated by a fixed shape keel is independent of u in the turbulent conditions, consistent with the attenuation after passing through the shelterbelt for different wind speeds (Ozawa et al., 2007) and the review of sheltering behind sand fences (Li & Sherman, 2015). Therefore, it is reasonable to assume that the errors introduced by differences in the upper boundary are small and do not significantly impact the form or accuracy of the sheltering function.

Secondly, compared to the natural conditions in the Arctic Ocean where $D \gg H$, the shallow water in the experimental tank has led to increased sheltering. To better understand this, we performed variable depth experiments with D varying from 0.30–0.50 when α= 45°, H = 0.12m. The resulting Γ vs. L/H is given in Fig. 13. The dark red curve represents the fit for D = 0.30 m (R^2 = 0.99), while the light red curve represents the fit for D = 0.50 m (R^2 = 0.98). The shallow depth may restrict the ability of wakes to expand vertically, inhibiting the spread of eddies along the depth direction and resulting in accelerated wake recovery (Ouro & Nishino, 2021; Singha et al., 2009; Akilli, & Rockwell, 2002). As a result of this feature, Γ gradually increased with decreasing D. D/H was not inserted in the form of the sheltering function but rather illustrated by the determination of its coefficients. No attempt has been made here to fit depth D into the sheltering function for this stage, because Γ is expected to be depth-independent beyond the critical depth (Zu et al., 2021). However, this does not deny the above evaluations of sea ice dynamic parameters in section 5.2. Because Fig. 12(a-c) was recalculated by using approximately 50% lower coefficients of the exponential function in Eq. (3), but the results revealed that the variation trend changed little and the maximum value of C_{io} increased only below 15%. The given portion 50% is roughly determined through linearly extending the form of $\Gamma_{D=0.3}$ and $\Gamma_{D=0.5}$ in Fig.13 to the critical depth in Zu et al. (2021).

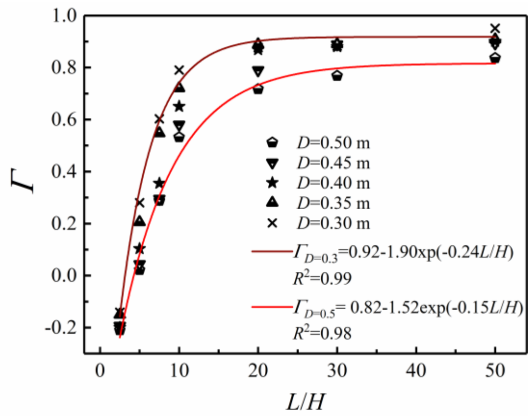

Fig. 13 The sheltering coefficient $\Gamma = \Gamma(L/H)$ when the tank depth D is increased from 0.30 m to 0.50 m at α = 45° and H=0.12 m (D/H=2.5-4.17). The dark red/light red curve represents the fit of Γ for D = 0.30 m/D = 0.50 m; R^2 = 0.99 and 0.98. The fits for the other D are similar, and not shown here.

Thirdly, the sheltering strength of the wake was overestimated in the far-wake region (L/H > 30). Asymptotically, the sheltering function approached a limit less than 1, within 0.82–0.97 in Fig. 11. This was somewhat different from our intuition and was caused by the nature of laboratory experiments where the system is forced by the inflow boundary condition. The flow section in the tank was 11 m long inevitably experienced a loss of flow velocity and the floating free surface which may result in Γ < 1. Since the momentum was fed into the system from the boundary, passing a keel resulted in a loss of momentum due to the form drag. Consequently, the drag force was lower than expected at keel-2, with Γ<1. In nature, momentum is fed into the system by distributed forcing over the whole ice cover, and a corresponding momentum loss does not occur. Thus, when the ridge spacing tends to infinity, the downstream keel drag force is not affected by upstream sheltering, corresponding to Γ=1.

5 Conclusion

Laboratory experiments were carried out to investigate the form drag of adjacent sea ice ridges and the sheltering effect of varying keel depth H, dimensionless spacing L/H, keel slope angle α, and flow velocity u. The conclusions are drawn as below.

The drag force F_1 on the upstream keel exhibited stability as L/H increased and was close to the case of an individual keel; just within L/H <10, F_1 increased by 5% due to the presence of downstream keel. The drag force F_2 on the downstream keel became larger with increasing L/H and gradually approached an asymptote. At $L/H \leq$ 10, F_2 was opposite to the flow direction, as the downstream keel was located within the recirculation zone created by the upstream one. F_2 was proportional to the square of u, consistent with the classical drag force formula.

The sheltering coefficient $\Gamma = F_2/F_1$ characterises the sheltering strength. Γ is related to L/H and α but is independent of u. A new formula was proposed by fitting the experimental results: $\Gamma = [1\text{-}1.56\exp(sL/H)]\times1.20\alpha^{-0.08}$, $s = 0.001\alpha\text{-}0.15$; s was changed from a constant to a linear function of α. Overall, the function can be treated as the product of an exponential function and a power function. On the one hand, there is an exponential relationship between Γ and L/H. Γ increased as the L/H increases and underwent the transition from negative to positive at L/H = 5. The time-averaged streamlines, turbulent kinetic energies and Reynolds stresses for L/H = 5 and L/H = 10, corresponding to the single body regime and the reattached flow regime, were calculated using the PIV results to validate the effect of L/H variations on wake turbulence characteristics. On the other hand, there is a power relationship between Γ and α which is characterised a decreasing trend as α increases. By comparing the flow flied results for α = 20°, 45° and 60°, the wake expanded longitudinally as the angle increased, accompanied by larger recirculation zone, stronger TKE, and greater Reynolds stress. However, the influence of α on Γ was also coupled with L/H. α was mostly impactful in the near-wake region.

A sea ice free-drift dynamics case was calculated using three different sheltering function. The differences in results of C_{io}, wind factor $|u_i|/|u_a|$ and the deflection angle θ are more pronounced at $H/L \geq 0.01$, corresponding to more dense ridged ice nowadays in observations than before (Berner et al. 2021; Davis & Wadhams, 1995). The values calculated using the new sheltering function are larger than the power function, smaller than the exponential function. The coupling of H/L and α leads to a non-linear variation of C_{io}, $|u_i|/ |u_a|$ and θ at $H/L \geq 0.01$, however, the remaining two functions could not to capture this feature. In the range of $0.05 \leq H/L \leq 0.1$, the sheltering strength is enhanced and $|u_i|/ |u_a|$ increases from 0.012 to 0.024 when α increased from 10 to 90°. It is contrast to a constant wind factor for different ridge slope as using previous sheltering functions.

As a solid step towards the final objective of parameterization, the new function has a clear physical meaning that incorporates both the impact of the dimensionless spacing and slope angle on the sheltering, which is an improvement of the previous results by Steele et al. (1989). The outcome has clarified the major parameters affecting sheltering as well as the turbulent structure and characteristics of the flow field around double keels. Because of the limitations from water tank experiments, Eq. (3) cannot be further optimised and then directly applied to the polar ocean. However, it can be straightforwardly improved and extended to depth-independent situations using numerical simulations in the next step. Possible directions of future research include, but are not limited to, (i) considering the probability distribution function of geometric parameters and spacings of ice ridges, (ii) considering the porosity of ice ridges, and (iii) probing the mechanisms of variation in shelter effects in a stratified two-layer flow. It is anticipated that a universal relationship can be obtained that is applicable in sea ice dynamics modelling.

Acknowledgements

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Data Availability Statement

The laboratory experiment data include drag force measurements and PIV flow field measurements shown in this manuscript can be accessed via the website (https://doi.org/10.5281/zenodo.10065506)

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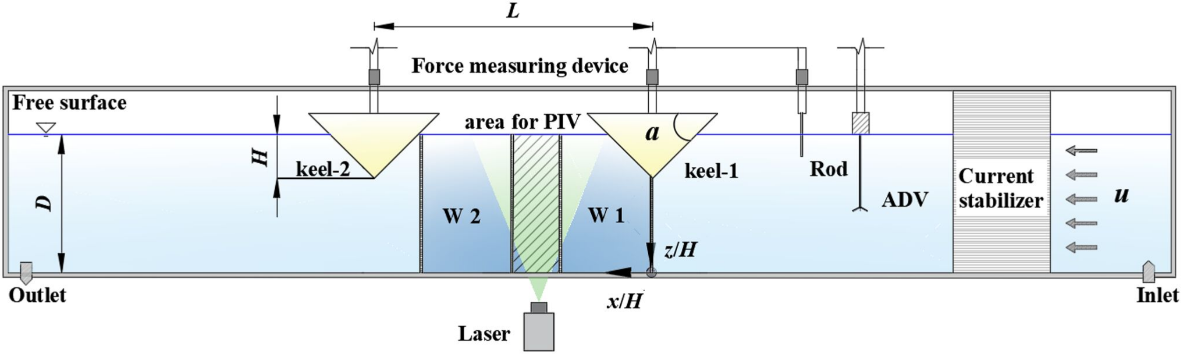
Figure 1.

(a)



L
Force measuring device
Free surface
area for PIV
H
a
keel-2
keel-1
Rod
Current
stabilizer
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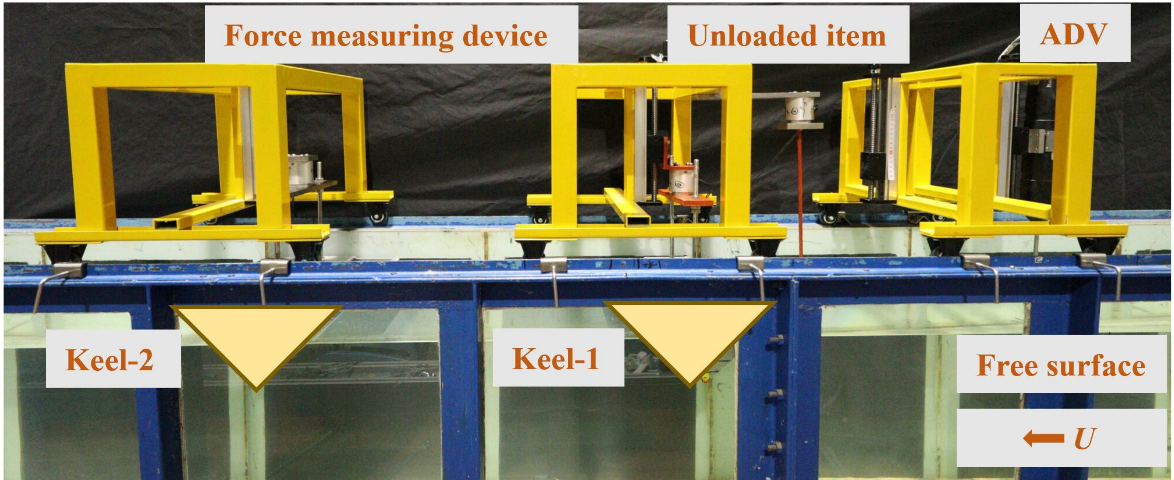
W 2
W 1
z/H
Outlet
x/H
Inlet
Laser

(b)



Force measuring device
Unloaded item
ADV
Keel-2
Keel-1
Free surface
U

Figure 2.

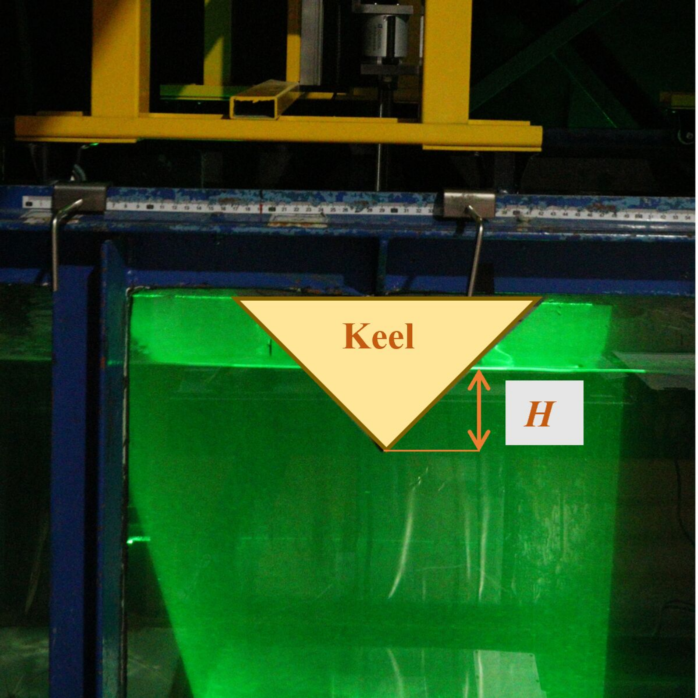

Keel
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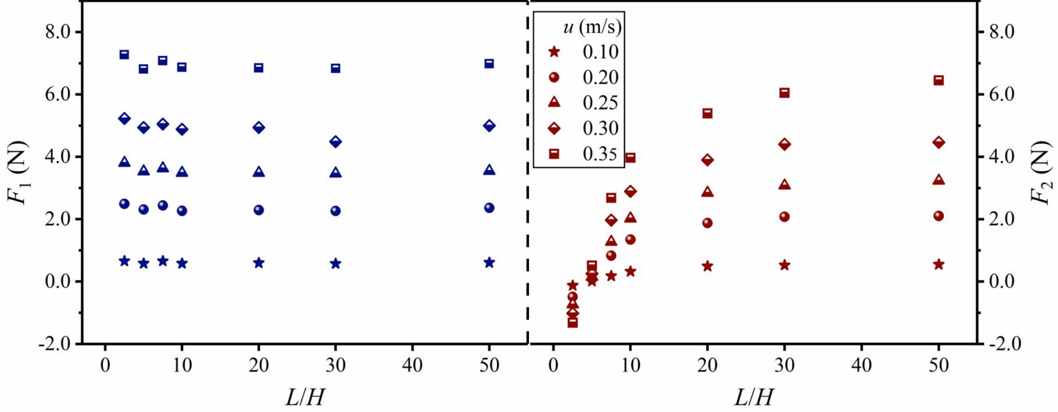
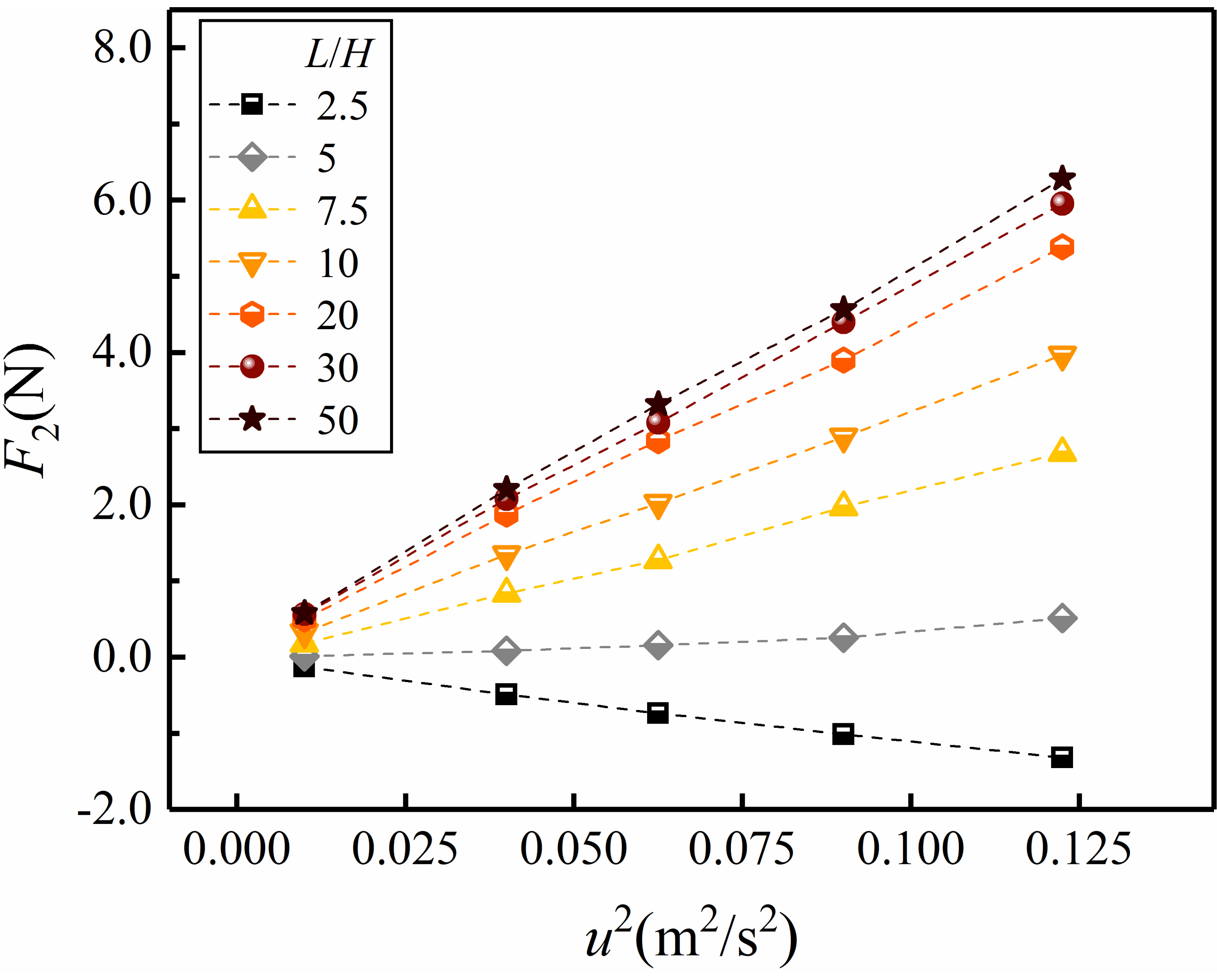
Figure 3.



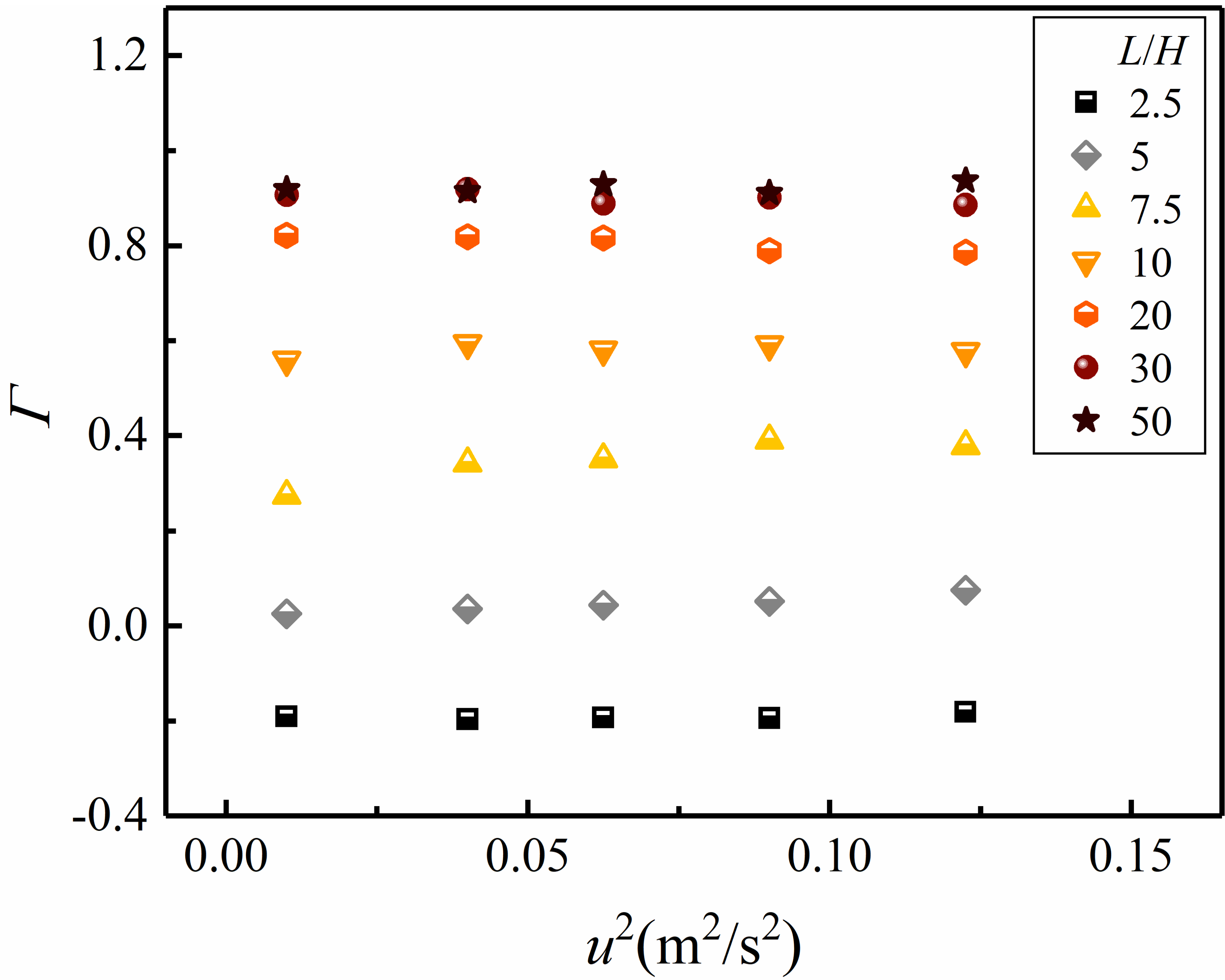
u (m/s)
0.10
0.20
0.25
0.30
0.35
F1 (N)
F2 (N)
L/H
L/H
8.0
6.0
4.0
2.0
0.0
-2.0
0
10
20
30
40
50

Figure 4.



L/H
2.5
5
7.5
10
20
30
50
8.0
6.0
4.0
2.0
0.0
-2.0
0.000
0.025
0.050
0.075
0.100
0.125
F_2(N)
u^2(m^2/s^2)

Figure 5.



L/H
2.5
5
7.5
10
20
30
50
1.2
0.8
0.4
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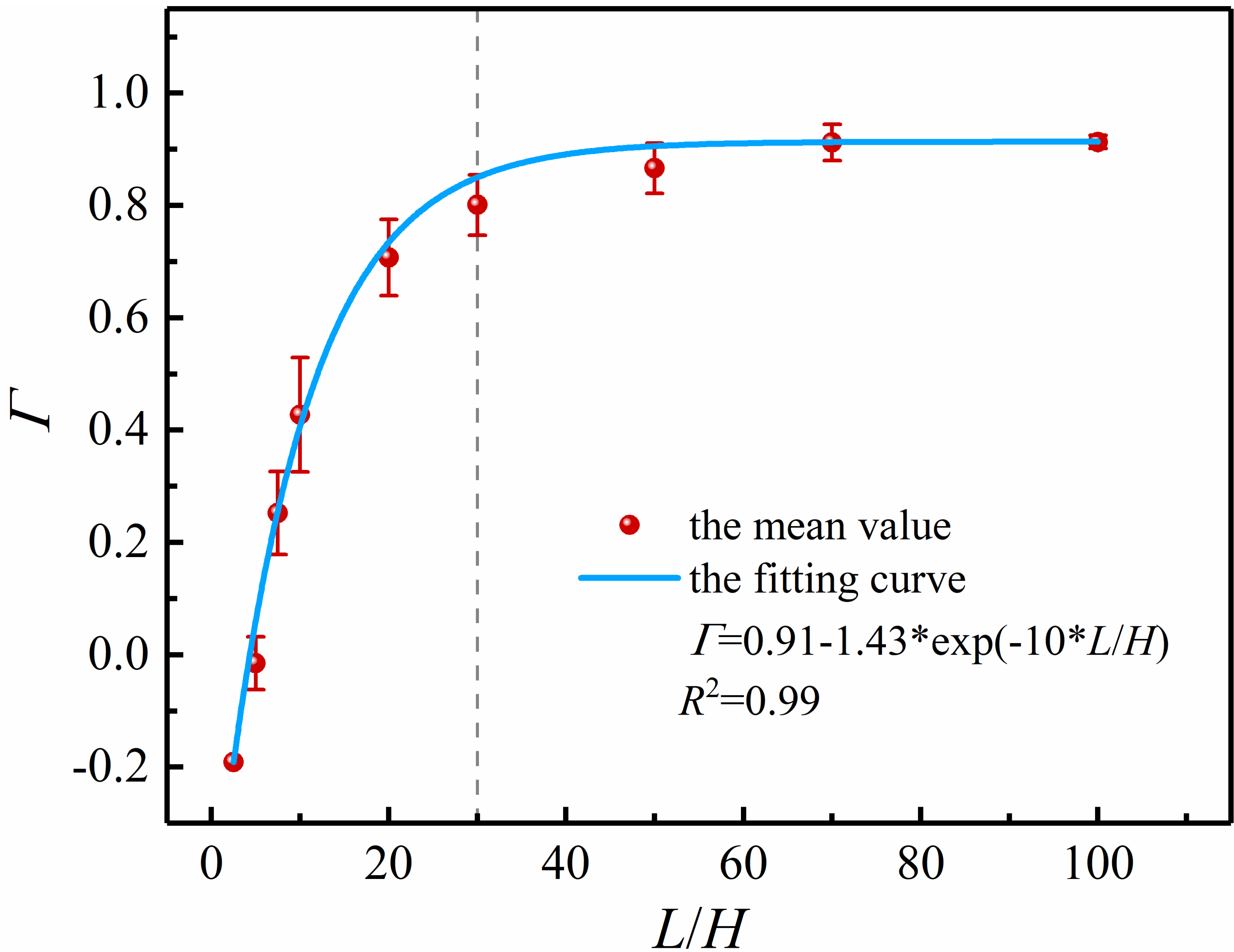
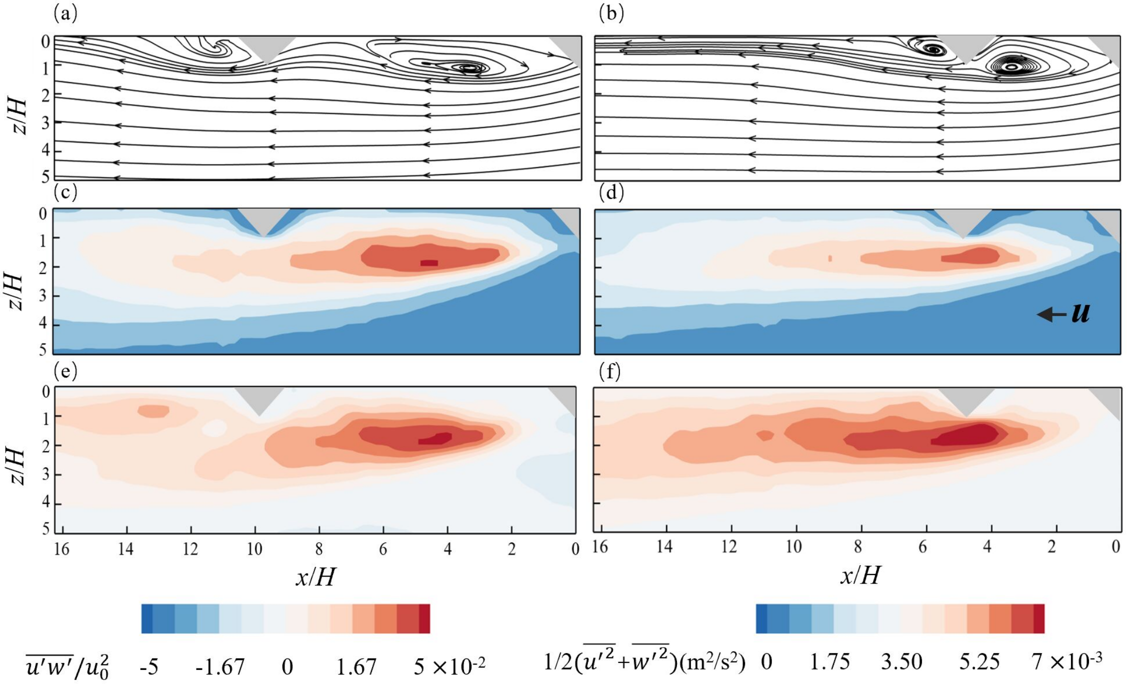
0.00
0.05
0.10
0.15
u^2(m^2/s^2)

Figure 6.



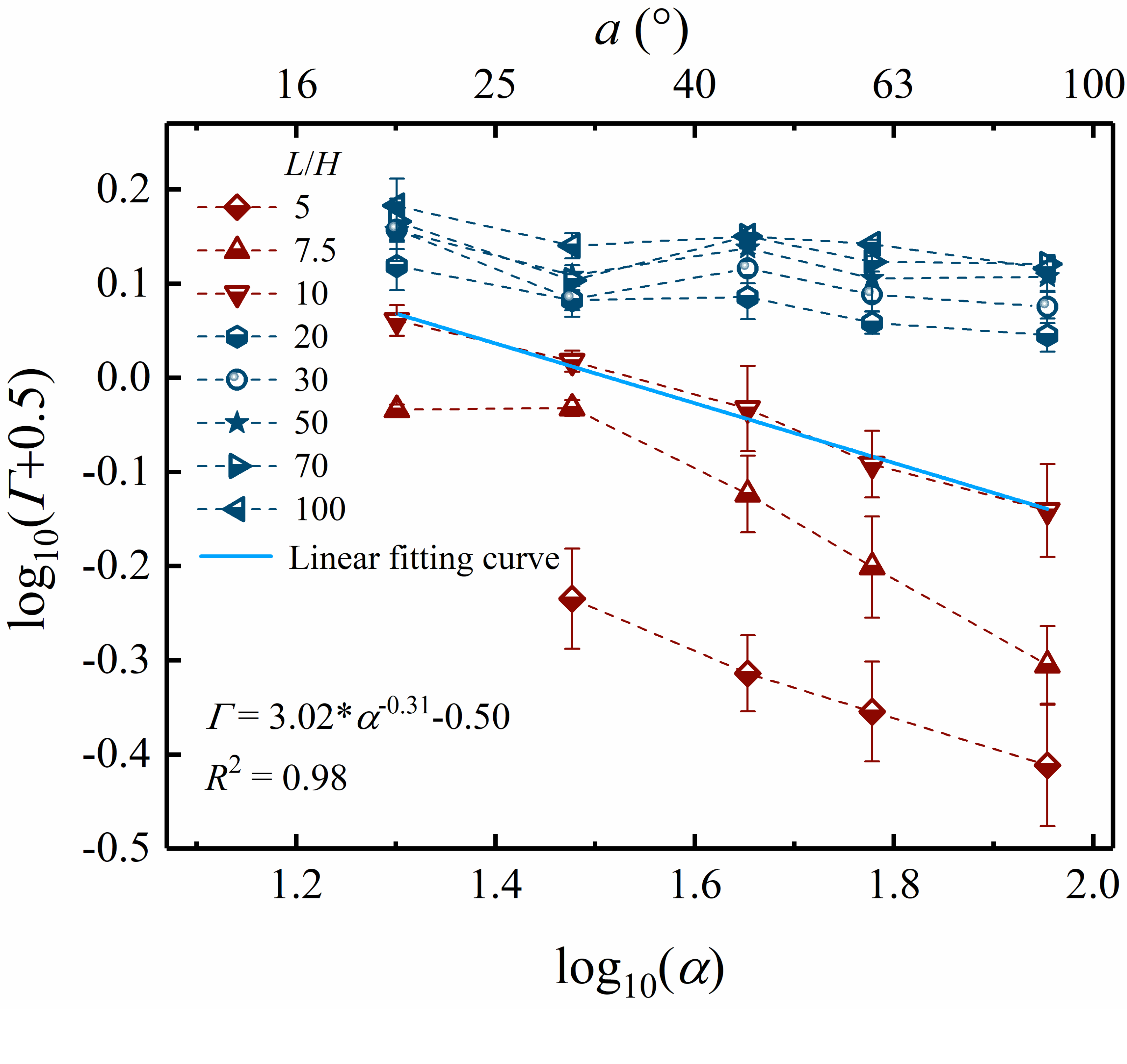
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Γ
0
20
40
60
80
100
L/H
the mean value
the fitting curve
Γ=0.91-1.43*exp(-10*L/H)
R2=0.99

Figure 7.



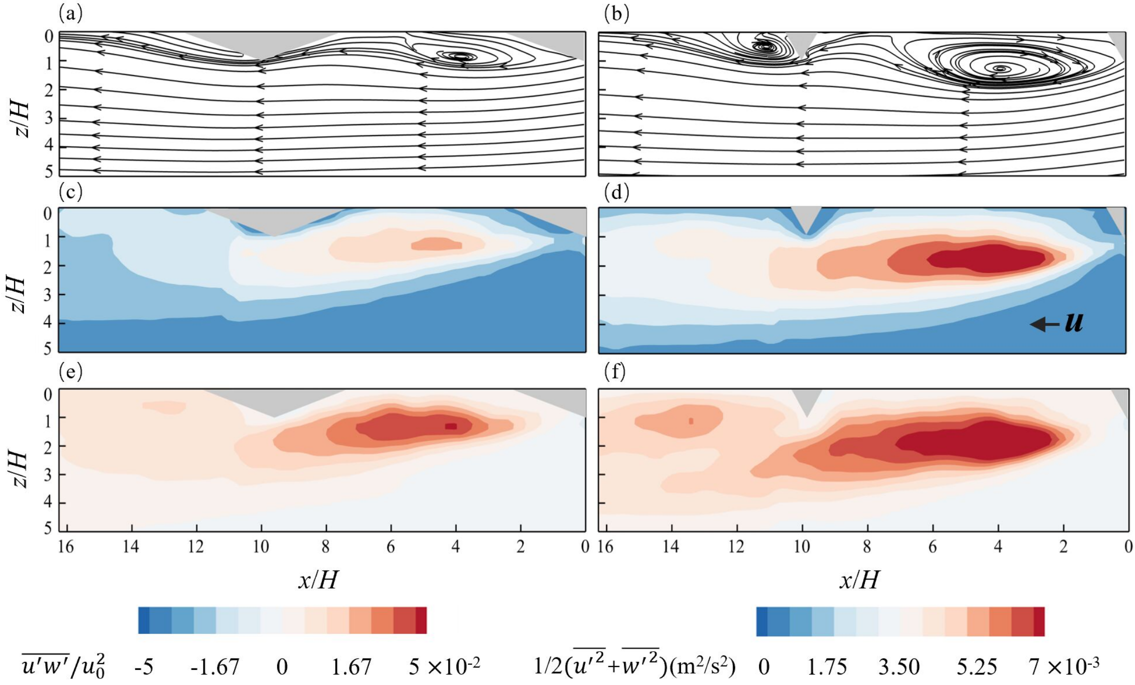
(a)
(b)
(c)
(d)
(e)
(f)
z/H
x/H
u
$\overline{u'w'}/u_0^2$ -5 -1.67 0 1.67 5 ×10⁻²
$1/2(\overline{u'^2}+\overline{w'^2})(m^2/s^2)$ 0 1.75 3.50 5.25 7 ×10⁻³

Figure 8.



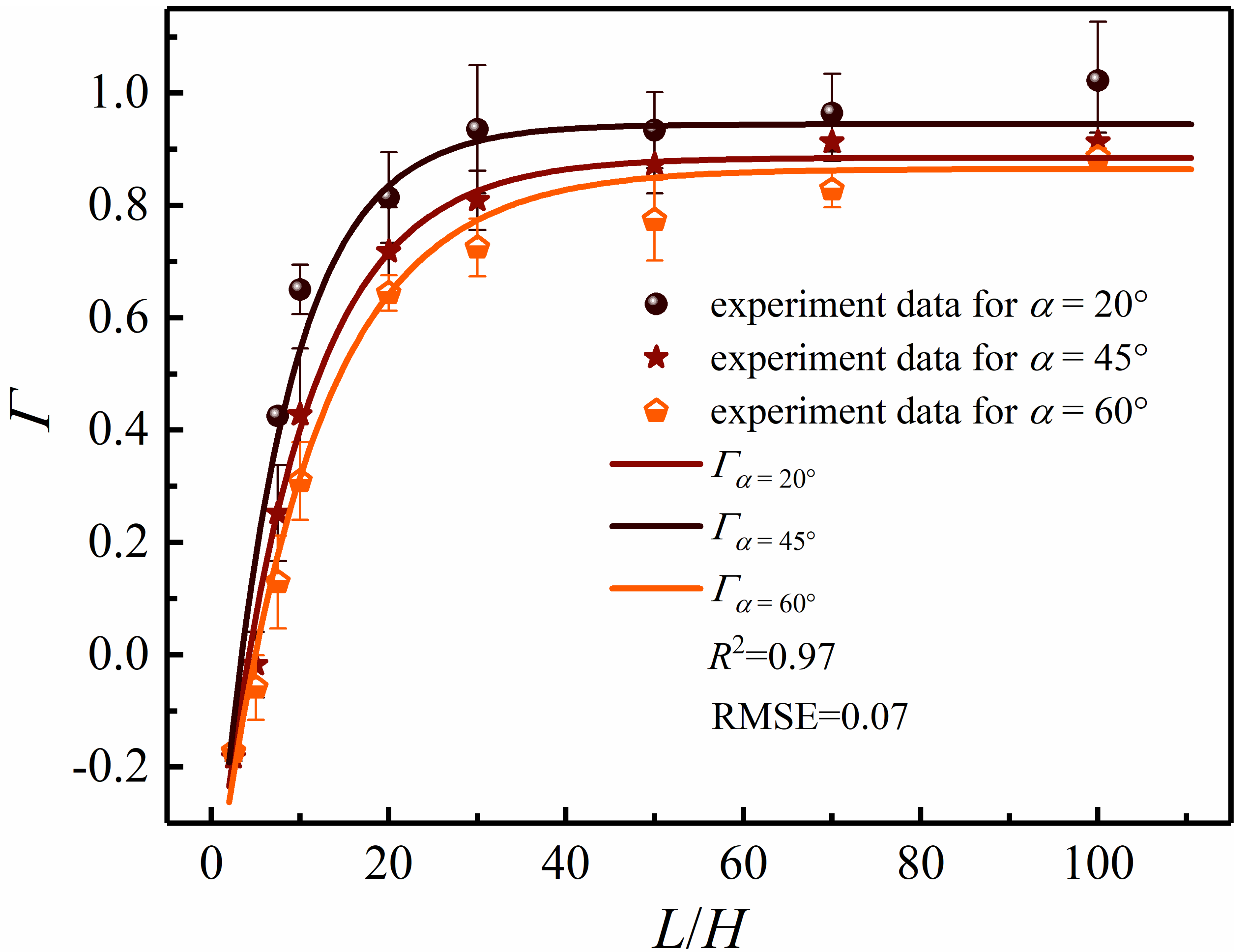
a (°)
16
25
40
63
100
L/H
5
7.5
10
20
30
50
70
100
Linear fitting curve
$\Gamma = 3.02*\alpha^{-0.31}-0.50$
$R^2 = 0.98$
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
$\log_{10}(\Gamma+0.5)$
1.2
1.4
1.6
1.8
2.0
$\log_{10}(\alpha)$

Figure 9.



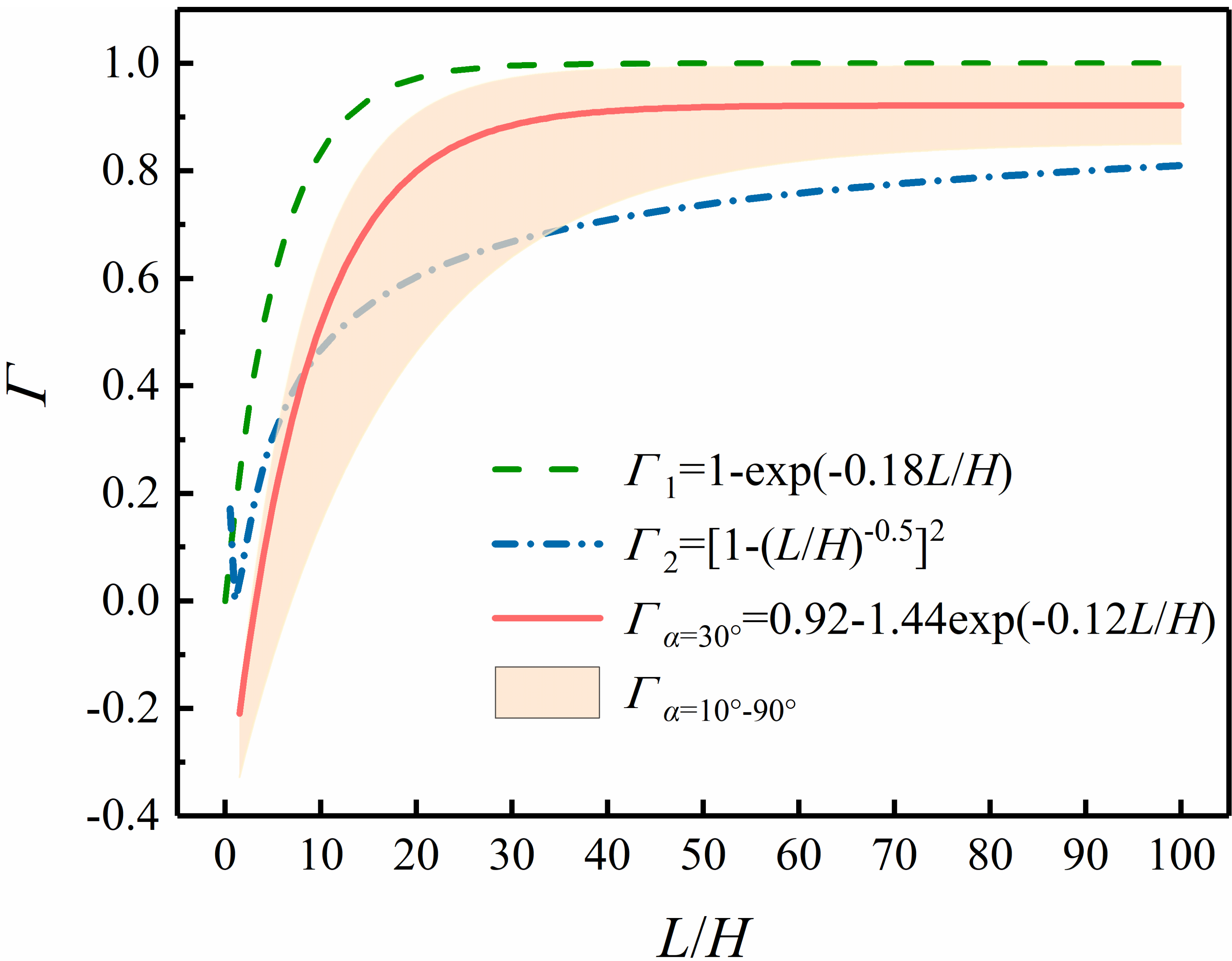
(a)
(b)
(c)
(d)
(e)
(f)
z/H
x/H
u
$\overline{u'w'}/u_0^2$ -5 -1.67 0 1.67 5 ×10-2
$1/2(\overline{u'^2}+\overline{w'^2})$(m2/s2) 0 1.75 3.50 5.25 7 ×10-3

Figure 10.



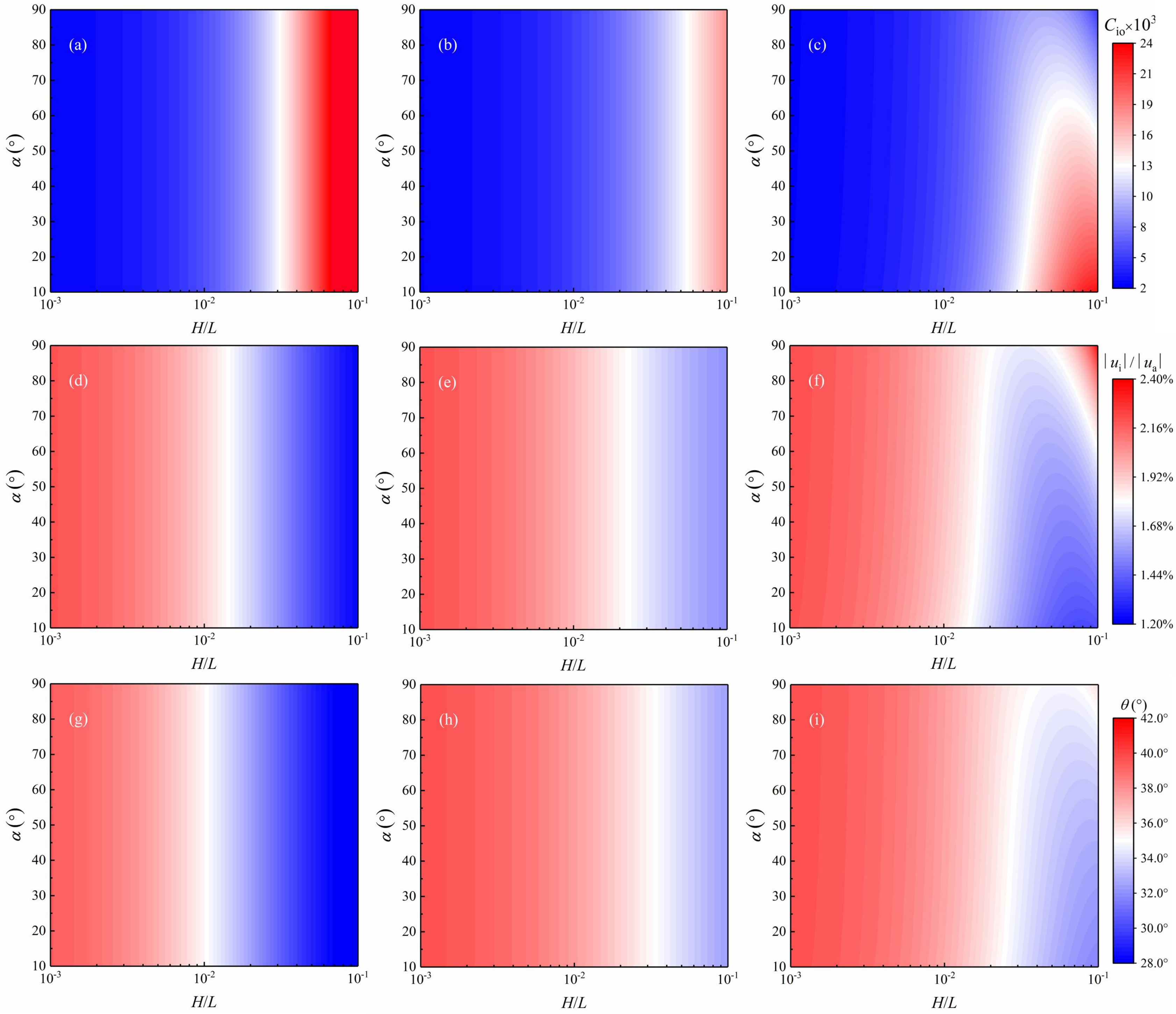
Γ
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
20
40
60
80
100
L/H
experiment data for $\alpha = 20°$
experiment data for $\alpha = 45°$
experiment data for $\alpha = 60°$
$\Gamma_{\alpha = 20°}$
$\Gamma_{\alpha = 45°}$
$\Gamma_{\alpha = 60°}$
R^2=0.97
RMSE=0.07

Figure 11.



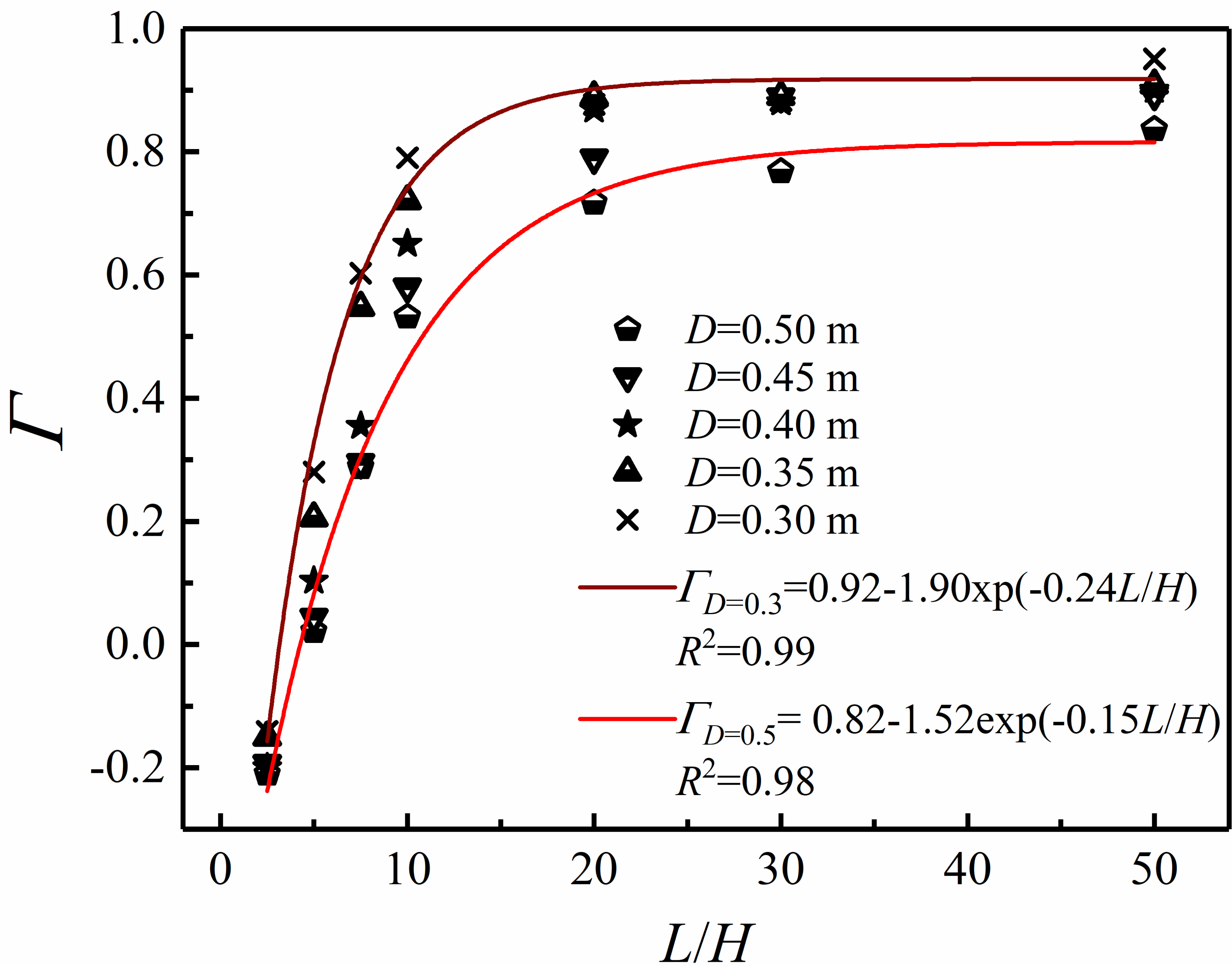
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
10
20
30
40
50
60
70
80
90
100
Γ
L/H
Γ1=1-exp(-0.18L/H)
Γ2=[1-(L/H)-0.5]2
Γα=30°=0.92-1.44exp(-0.12L/H)
Γα=10°-90°

Figure 12.



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
$C_{io} \times 10^3$
24
21
19
16
13
10
8
5
2
$|u_i| / |u_a|$
2.40%
2.16%
1.92%
1.68%
1.44%
1.20%
$\theta (°)$
42.0°
40.0°
38.0°
36.0°
34.0°
32.0°
30.0°
28.0°
$\alpha (°)$
H/L
10^{-3}
10^{-2}
10^{-1}

Figure 13.



1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Γ
0
10
20
30
40
50
L/H
D=0.50 m
D=0.45 m
D=0.40 m
D=0.35 m
D=0.30 m
$\Gamma_{D=0.3}$=0.92-1.90xp(-0.24L/H)
R^2=0.99
$\Gamma_{D=0.5}$= 0.82-1.52exp(-0.15L/H)
R^2=0.98