Quantifying the Effect of Aquatic Vegetation on Interfacial Gas Transfer in Streams

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Abstract

Turbulence generated by aquatic vegetation in rivers, lakes, and estuaries, can significantly alter the flow structure throughout the whole water column, affecting gas transfer mechanisms at the air-water interface, driving changes in indicators of water quality. We conducted a series of laboratory experiments with rigid cylinder arrays to mimic vegetation using a staggered configuration in a recirculating Odell-Kovasznay type race-track flume. 2D planar Particle Image Velocimetry (PIV) was used to characterize the mean flow field and turbulent flow statistics, to characterize the effect of emergent and submerged vegetation in terms of turbulent kinetic energy, Reynolds stresses, and turbulent shear production. The surface gas transfer rate was determined by measuring the dissolved oxygen (DO) concentration during the re-aeration process in water based on the methodology proposed by the American Society of Civil Engineers (ASCE). Our data provide new insight on how stem- and canopy- scale turbulence affect the surface gas transfer rate at different submergence ratios and array densities. The relation between mean flow velocity and turbulent shear production in these scenarios is used to develop a modified surface renewal (SR) model using turbulent shear production as an indicator of gas transfer efficiency, which allows us to more accurately predict surface gas transfer rates in vegetated flows.

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Abstract

- Turbulence generated by aquatic vegetation can alter flow structures throughout the whole water column, affecting gas transfer mechanisms at the air-water interface (Fig. 1).

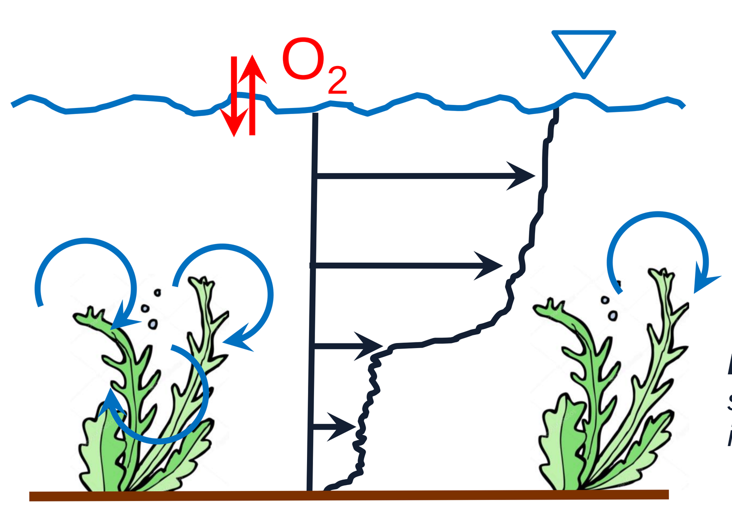

Figure 1. Sketch of surface gas transfer in vegetated flows.

- A series of laboratory experiments were conducted with arrays of acrylic cylinders in a recirculating race-track flume, using PIV for flow characterization within and above the array.
- Surface gas transfer rates were determined by measuring the dissolved oxygen (DO) concentration during the re-aeration process in water.
- Our data show how stem- and canopy- scale turbulence affect surface gas transfer rates at different submergence ratios and array densities.
- A modified surface renewal (SR) model is developed to more accurately predict surface gas transfer rates in vegetated flows.

Methodology

- Experiments are conducted on a recirculating race-track flume, using dense and sparse ($ah = 0.5 \,\&\, 0.1$) staggered arrays of cylinders to mimic aquatic vegetation (Fig. 2).
- 2D-PIV is used to characterize the flow field (PIV - 5W CW Laser, 5MP 60fps camera).
- Flow conditions vary from emergent to fully submerged arrays, $h/H = \{1, 0.5, 0.25\}$.
- A frequency controlled (10-40 Hz) disk pump drives the flow for a velocity range $\overline{U} = \{1-22\} cm/s$, yielding $Re_d = \{60-660\}$, $Re_H = \{600-13{,}000\}$.
- By using Sodium Sulfite (Na_2SO_3) as an oxygen depletion agent, surface gas transfer rates can be fitted by DO re-aeration curves in water.

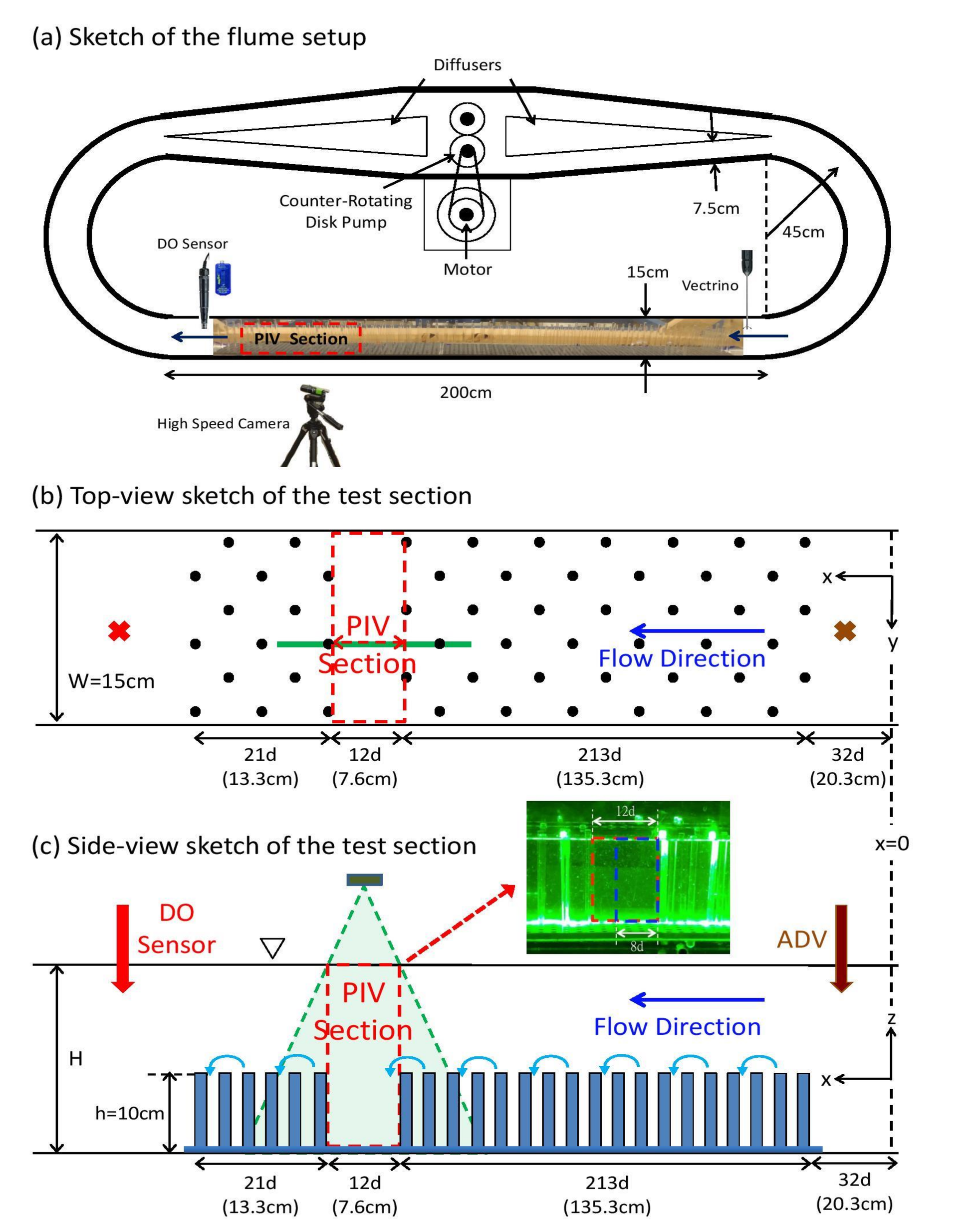

Figure 2. (a) Sketch of the recirculating racetrack flume. Top- (b) and side-view (c) sketch of the vegetation array (not to scale). Cross signs are for ADV (upstream) and DO (downstream) locations.

Results and discussion

- **Flow velocity structure:**
  - Uniform velocity distribution within the canopy.
  - Sharp velocity gradient on top of the submerged canopy.

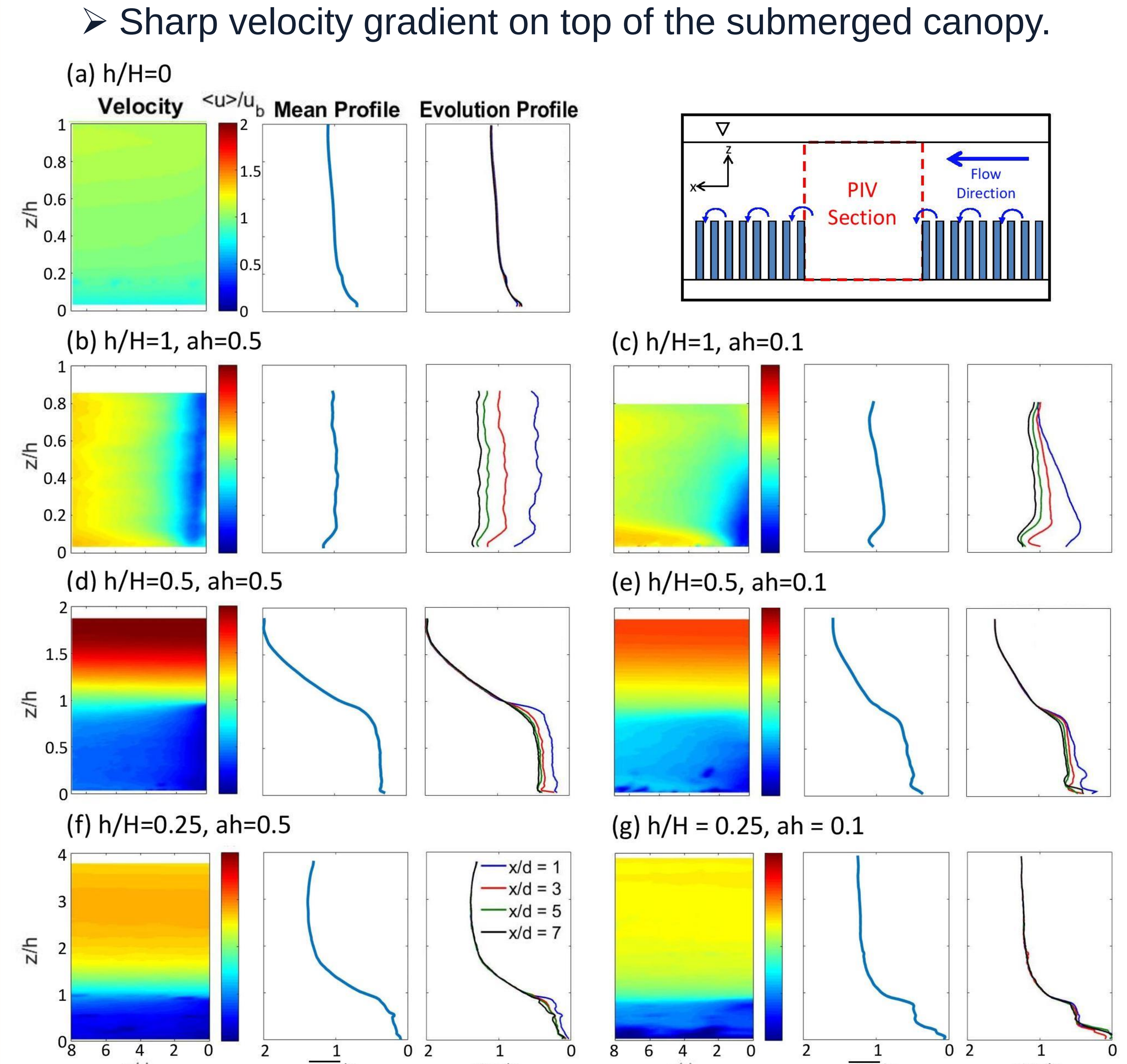

Figure 3. The normalized velocity field, mean velocity profiles, and evolution profiles with different roughness density, ah, and submergence ratio, h/H, under inverter frequency f = 30 Hz. Velocity is normalized by the time-averaged bulk velocity U_b. The corresponding U_b and mean flow Reynolds number, Re_H, for cases (a) - (g) are U_b = {12.1, 3.4, 5.2, 9.9, 11.6, 14.8, 15.8} cm/s, and Re_H = {4.9, 1.8, 3.2, 5.6, 7.1, 9.4, 10.4} x10^3, respectively.

- **Turbulence Statistics:**
  - TKE $= 0.5\left(2\langle u'^2\rangle + \langle w'^2\rangle\right)$.
  - TKE production, $P = \langle u'w'\rangle \frac{\partial\langle u\rangle}{\partial z}$.
  - Bulk mean shear velocity $u_b^* = \sqrt{-\langle u'w'\rangle_b}$.

    Maximum shear velocity $u_{max}^* = \sqrt{-\overline{\langle u'w'\rangle}_{max}}$.
  - Stem-scale turbulence dominates the mixing and exchange processes within the canopy.
  - Canopy-scale turbulence dominates the mixing and exchange processes above the canopy.

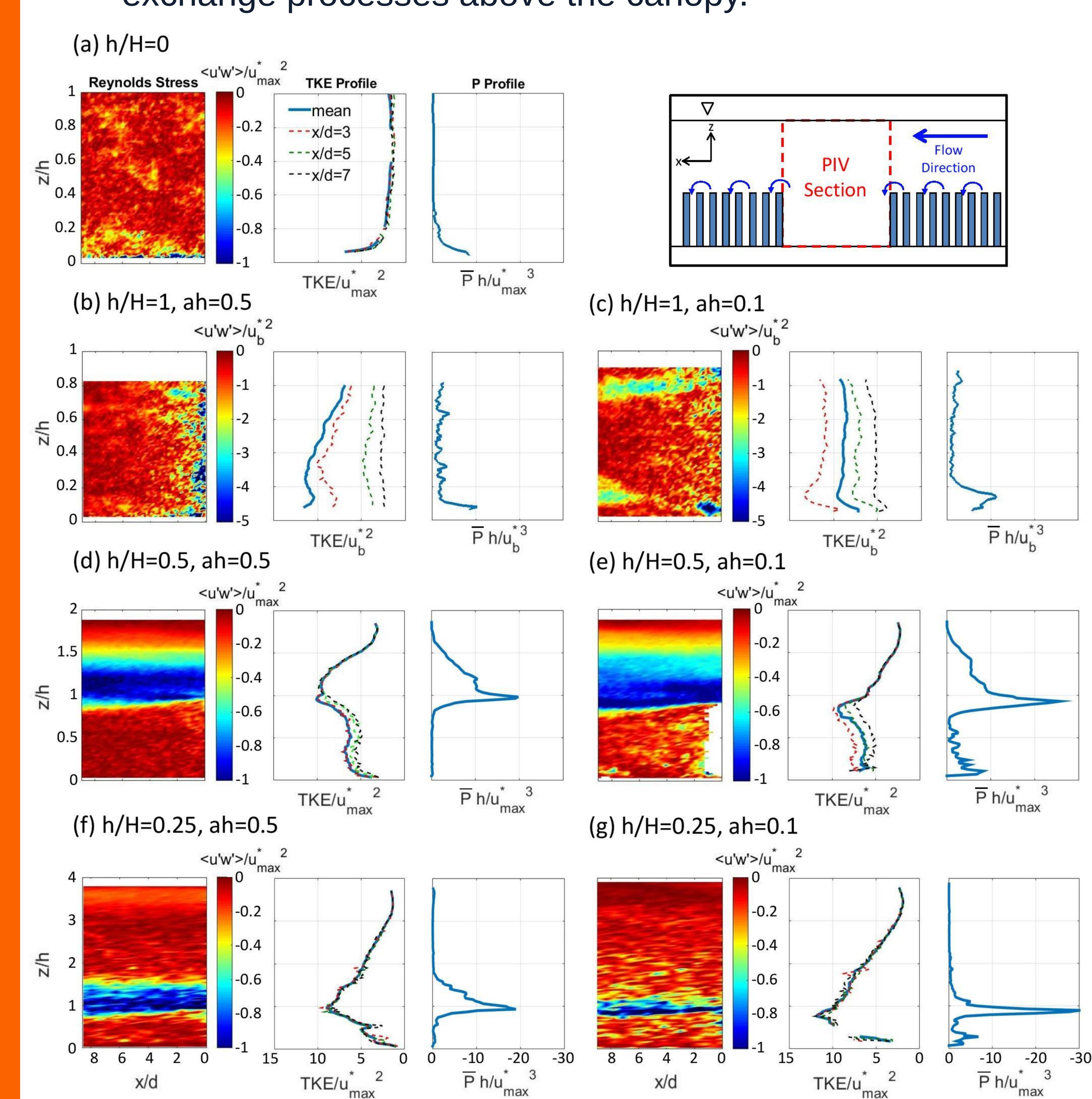

Figure 4. The normalized Reynolds stress field, TKE profiles, and streamwise-averaged TKE production profiles with different roughness density, ah, and submergence ratio, h/H, under inverter frequency f = 30 Hz. The above values are normalized by using the vegetation height, h, and the characteristic shear velocity, u^*_c ($u^*_c = u^*_b$ for emergent cases, $u_c^* = u^*_{max}$ for submerged cases). The corresponding U_b and mean flow Reynolds number, Re_H, for cases (a) - (g) are the same as Figure 3.

- **TKE production dependence on mean flows:**
  - $P_b = C_{eme} {u_b}^3$, $\bar{P}_{max} = C_{sub} {u_b}^3$.

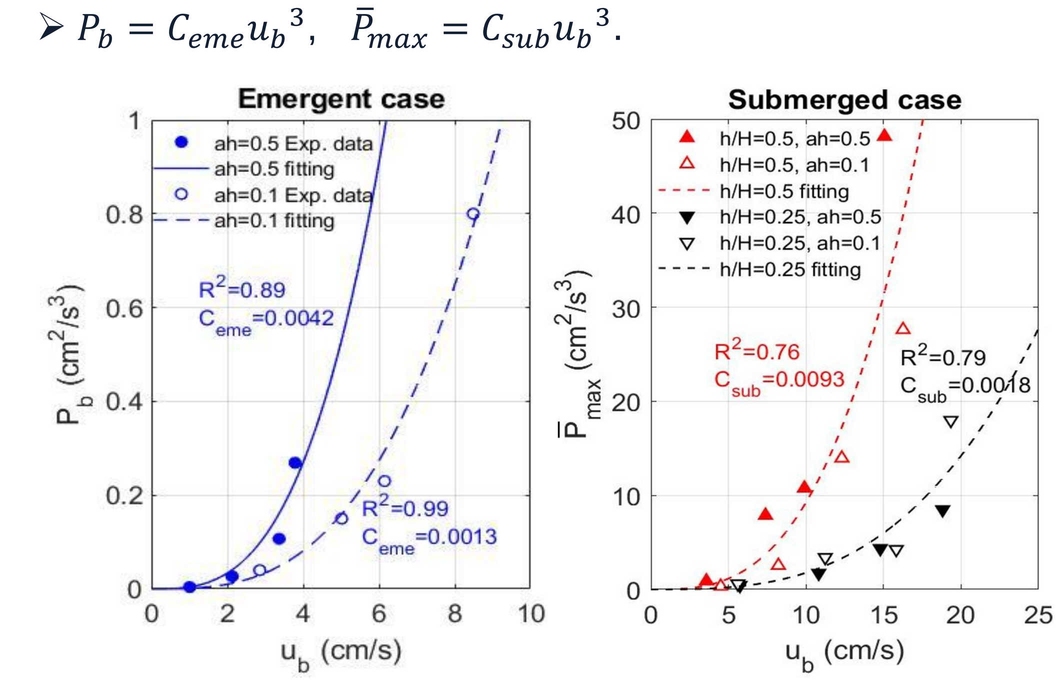

Figure 5. The relation between bulk TKE production, P_b, and u_b in emergent canopies (left). The relation between maximum TKE production, $\bar{P}_{max}$, and u_b in submerged canopies (right).

- **Gas transfer rates dependence on mean flows:**
  - TKE production plays a key role to connect mean flow rates to surface gas transfer mechanisms.

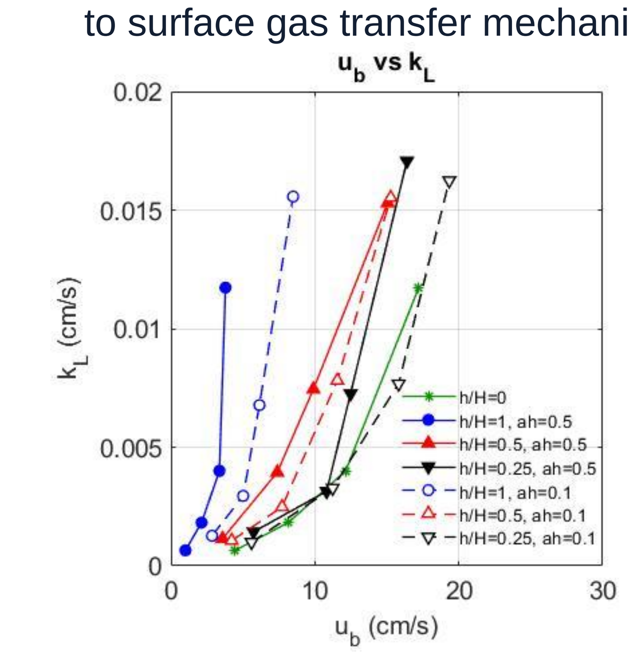

Figure 6. The relations between gas transfer rate, k_L, and the time-averaged bulk flow velocity, u_b, under different submergence ratios, h/H, and array roughness densities, ah. Solid and open symbols denote dense (ah = 0.5) and sparse (ah = 0.1) conditions, respectively.

- **Modified SR model for vegetated flows:**
  - General form: $k_L = \alpha\sqrt{L^+ \frac{D P_*^{1/2}}{\nu^{1/2}}}$.
  - Emergent cases: $P_* = P_b$, $L^+ = L^+_{eme} = Re_d^{1/2} \frac{H^{1/2}}{d^{1/2}} \frac{u_b^{*1/2}}{u_b^{1/2}}$.
  - Submerged cases: $P_* = \bar{P}_{max}$, $L^+ = L^+_{sub} = Re_H^{1/2} \frac{L_{up}^{1/2}}{H^{1/2}} \frac{u_{max}^{*1/2}}{u_b^{1/2}}$.
  - Fig.7 shows the slope changes after critical points, which infers a transition under those flow conditions.

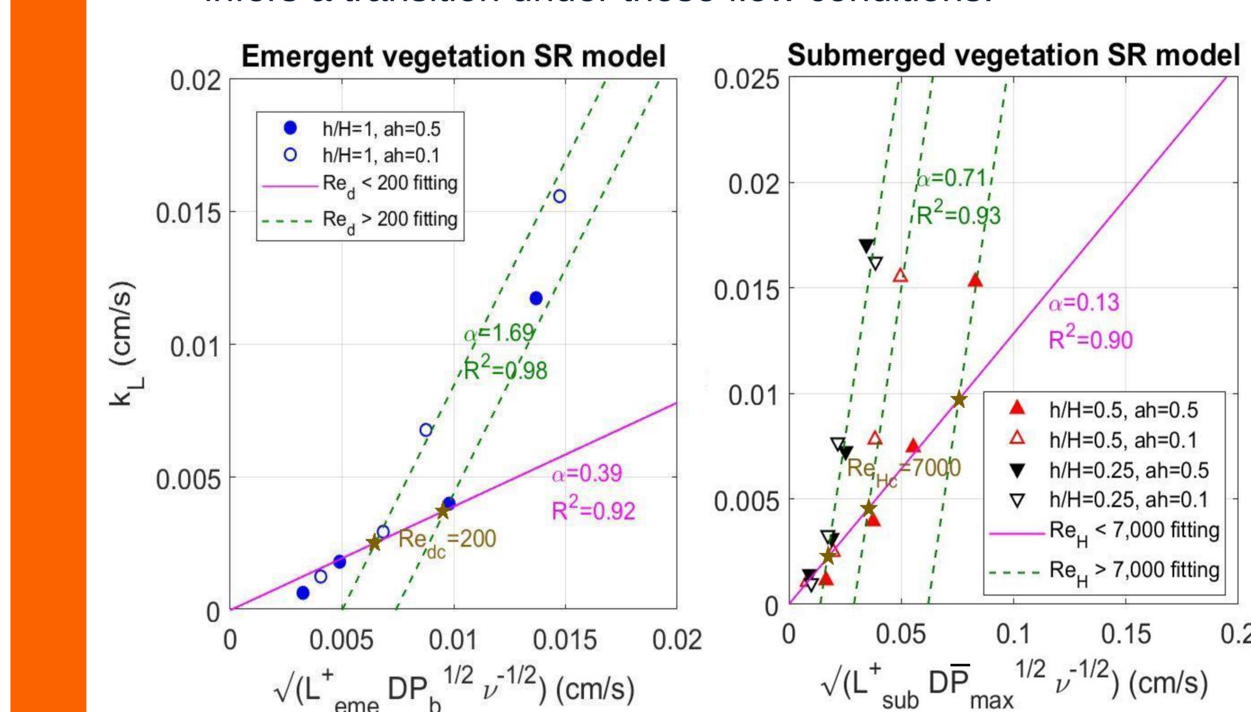

Figure 7. The linear fitting results of the emergent (left) and submerged (right) canopy data by the modified SR model. The critical stem-scale Reynolds number, Re_{dc}, for the emergent case is found around 200, while the critical mean flow Reynolds number, Re_{Hc}, is found around 7, 000. The star signs represent expected turning points (Re_d = 200, Re_H = 7, 000) for each case based on the model fitting result.

Conclusions

- Compared to the original SR model which doesn't consider any specific information of turbulence generated by vegetation, the new modified SR model using TKE production as an indicator allows us to more accurately predict surface gas transfer rates in vegetated flows under different submergence conditions.
- Stem- or canopy-scale turbulence plays an important role on enhancing surface gas transfer when the plant canopy is emergent or submerged, respectively.
- A critical Reynolds number can be found based on different submergence conditions, indicating a transition of the exchange mechanism at the interface.