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Comparisons of Models for Thermal Internal Boundary Layer Height Based on Measurements of the Water Tank Experiment

Youn-Seo Koo* and Hee-Young Yoon
Department of Environmental Engineering, Anyang University

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Abstract

A Thermal Internal Boundary Layer (TIBL) develops over the landside from the coast due to the surface temperature difference between the land and the sea when the sea breeze forms. The TIBL plays an important role in determining the pollutant concentrations where the plume emitted from a tall stack near the coast fumigates to the ground. The fumigation results in the high ground level pollutant concentration. In order to access the fumigation more precisely, the TIBL model to determine the TIBL height from the available meteorological data is very important. The TIBL models available in the literature were analyzed to identify the suitable model to apply in the fumigation. The TIBL heights predicted by the existing models were compared with the measurements in the water tank experiment. The results show that the TIBL models by Raynor is appropriate to predict the height of TIBL.

Key words : Sea breeze, Thermal internal boundary layer, Fumigation

1. INTRODUCTION

The thermal internal boundary layer (TIBL) is formed during the day when cold stable airs flow from a large body of water onto a heated land by the sea breeze. Air advected by the sea-breeze is stably stratified by its passage over the relatively cold water surface. As this stable air passes over the land, it is heated from below, forming the unstable mixed layer, which begins at the shoreline and grows in depth with inland distance. Fig. 1 shows a typical TIBL along the inland distance. When the elevated plume contacts with the TIBL, the plume is down-mixed to the ground resulting in the high ground level concentration. Therefore, the precise prediction of the height of the TIBL under the given atmospheric conditions is very important to estimate the dispersion of the plume and calculate the ground level concentration at inland side (Koo and Reible, 1996; Garratt, 1990).

There were several models for the TIBL height along the inland distance. Of special interest is to find the best model to predict the TIBL height. The TIBL was experimentally reproduced in the water tank and the measured heights on the development of the TIBL along the inland were compared with the calculated results from several models in the literature to identify the best fit model.

2. TIBL MODEL

The key parameters controlling the height of the

*Corresponding author
koo@aycc.anyang.ac.kr

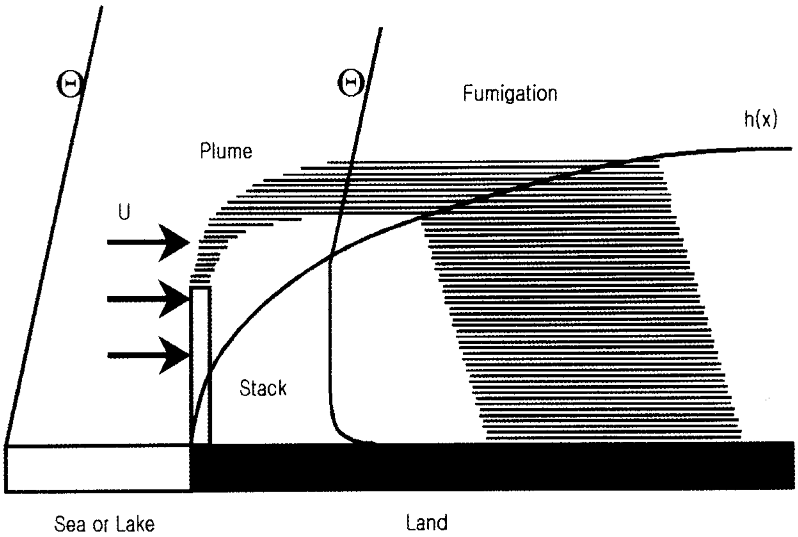

Fig. 1. Thermal internal boundary layer, h (x) and fumigation along the sea breeze (U is a wind velocity, Θ is a potential temperature, and h (x) is a thermal internal boundary layer height).

TIBL are the surface heat flux, wind speeds of sea breeze, the stratification of vertical temperature, and the temperature difference between the land and sea surface. The height grows with inland distance and the growth rate of TIBL is of importance in determining the location and spread of fumigation. The models for predict the TIBL height in the literature are discussed in the following.

Plate (1971) derived an equation for the TIBL height (h) from a heat balance:

$$h=\sqrt{\frac{4Qx}{\rho c_p \Gamma u}} \tag{1}$$

where Q is a surface heat flux from land, x represents the inland distance from the shoreline, ρ is the working fluid density, C_p is the fluid heat capacity, u is a wind speed of the sea breeze, and Γ is the vertical temperature gradient (i.e., vertical stratification). He assumed that the heat flux at the surface was constant and that the heat flux through the top of the TIBL was equal to the surface heat flux.

Weisman used the model equation similar to that of Plate (1971):

$$h=\sqrt{\frac{2Q_o x}{\rho c_p u (T_L-T_W)}} \tag{2}$$

It differs from the Plate (1971) equation by only a constant. The experimental observations will serve to differentiate between the two.

An equation based on the surface temperature difference between the land and sea was derived by Raynor *et al.* (1975):

$$h=\frac{u^*}{u}\sqrt{\frac{|T_L-T_W|x}{\Gamma}} \tag{3}$$

where T_L and T_W are the temperatures of the land and water surfaces, respectively, and u_* is the friction velocity, which represents the drag force by the change in surface roughness as the air flows from the sea to the land. This model for the TIBL height was the first to use the land and sea temperature difference to represent the driving force for the mixing layer formation.

Venkatram (1977) used a steady-state energy balance to derive an equation very similar to that of Raynor *et al.* (1975):

$$h=\frac{u^*}{u}\sqrt{\frac{2|T_L-T_W|x}{\Gamma(1-2F)}} \quad (4)$$

where F is an entrainment parameter approximately equal to 0.2. Venkatram (1977) notes that the value of this parameter has not been confirmed by observation but the prediction for the TIBL height is relatively insensitive to this value.

One aim of this study is to find the relationship between the TIBL height and the vertical stratification, heat flux, and inland distance as well as to determine the best model to predict the TIBL height among the four model explained above.

3. EXPERIMENTAL SETUPS

The schematic of the water tank experimental setups to simulate the sea breeze and the TIBL is shown in Fig. 2. The experiments were performed in a rectangular tank made of Lexan using water as the working fluid. The size of the tank was 120 (length) × 60 (width) × 60 (depth) cm. The 60 cm long and 15 cm wide heated plate to depict the land heating was used in the water tank. The details of setups of the water tank experiments and the procedure are found in Koo and Reible (1996). The water tank experiment to understand characteristics of buoyancy driven atmospheric flows was proved to be very effective tools and detailed design criteria for water tank experiment are also found in Hibberd and Sawford (1994). Similar water tank experiment for convective conditions are also found in Park *et al.* (1999, 2000). Since the present water tank experiment does not consider the Coriolis force in the development of sea breeze, the application of this study are limited to the flow and dispersion phenomena near the coast less than 10 km inland distance in the real atmosphere.

As the heat began on the heated plate, the small convective cells and strong vertical updrafts were formed over the surface of the heated plate, and the flows from the sea side then started to move to the landside from the edge of the heated plate. The front and circulation of the sea breeze became visible near the leading edge of the plate by forming the font, following flow behind the front, the return flow aloft toward the seaside.

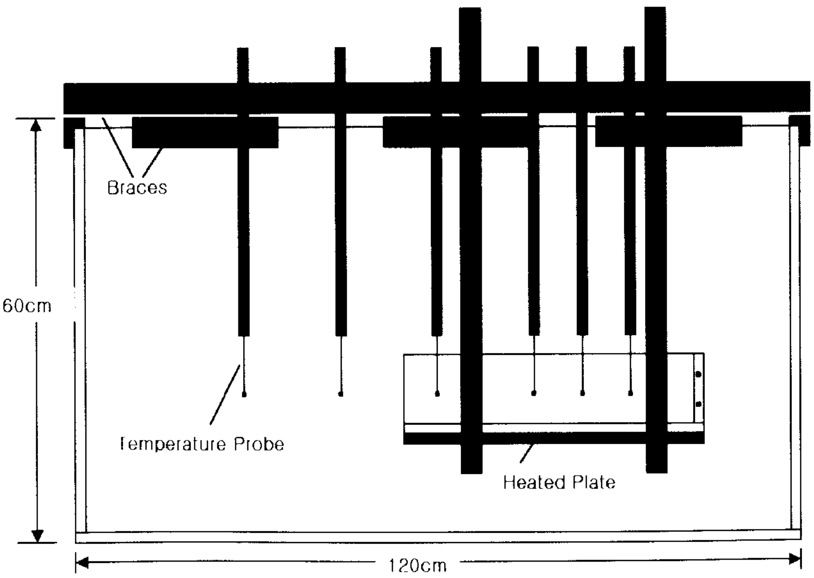

Fig. 2. A schematic of water tank used in the experiment.

Following the front, unheated water flowed onto the plate and was steadily heated as it passed over the plate. The dye was injected at the leading edge of the heated plate with a syringe as shown in Fig. 3(b) to visualize the TIBL height development. The dye injected was then moved along the heated plate and mixed vertically by convective eddy motion within TIBL and the depth of mixed layer was illuminated to measure the TIBL height. Fig. 3 shows the typical TIBL observed in the experiment. The reason to inject dye near the bottom was to observe the TIBL development from the coast line, which depicted as the leading edge of the heated plate in the experiment. This experiment was not designed to simulate the fumigation from the elevated source directly but to measure the TIBL height which was the key parameter in the fumigation assessment.

The top of the TIBL was judged to be the highest point reached by the dye. For each experiment, this height was measured at several points along the plate from videotapes of the experimental flows using the image analysis system. In addition to the dye visualization, the thermistors were used to measure the vertical stratification and to identify the TIBL height.

The velocity of the sea breeze, u, was measured by DPIV (Digital Particle Image Velocimetry) and the procedure was explained in Koo and Reible (1996) and the friction velocity was obtained from the measured vertical velocities assuming the logarithmic profile.

The experiments were designed to isolate and measure the effects of the heat flux and temperature stratification on the growth rate of the TIBL height. The

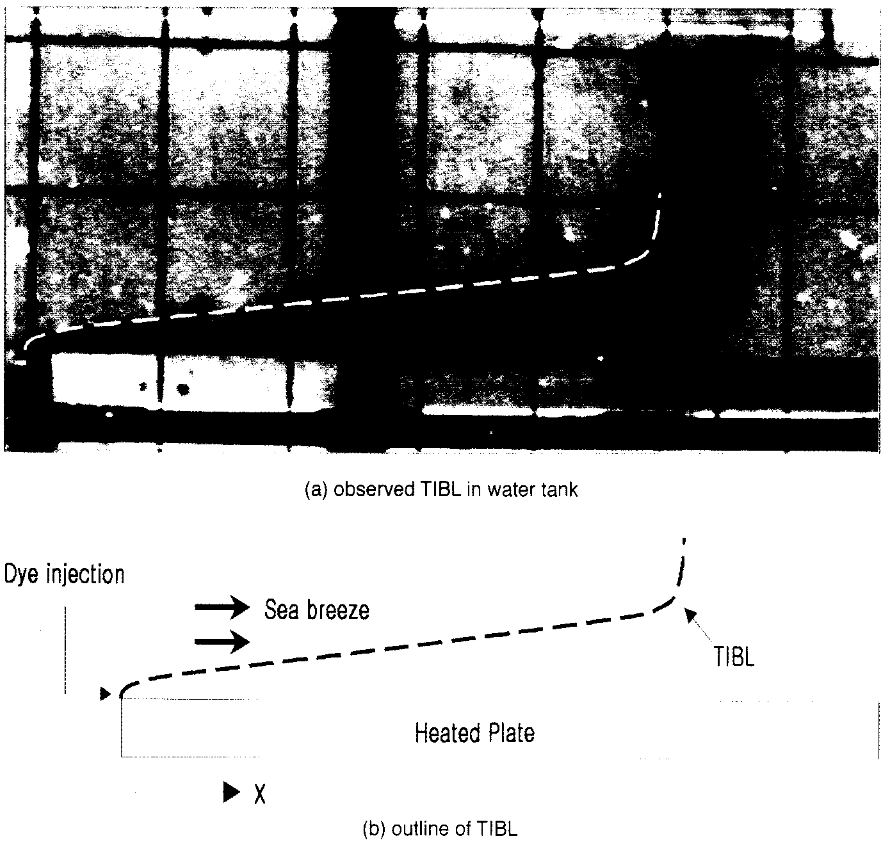

Fig. 3. A typical example of the dye visualization experiment for measuring TIBL height.

measurements of TIBL height under various conditions will be presented and compared with the models from the literature for predicting the height.

4. RESULTS AND DISCUSSIONS

There are several parameters to determine the TIBL height such as a temperature difference between the land and sea surface temperatures resulting from the sensible heating from the land, the thermal stratification, i.e., the vertical temperature lapse rate, the intensity of sea breeze. This study is of interested to investigate the influence of these parameters on the TIBL height and to find the proper equation to calculate the TIBL height. This study is not intended to coin new equation but select the best equation to depict the TIBL height proposed in the literature.

The TIBL height was found to grow with the square root of the inland distance in the experiments. Fig. 4 shows the measured dependence of the TIBL height, h (x), with the inland distance x. The figures demonstrates a reasonably good fit between the assumption of a square-root dependence as presented in the model and the measured values. Fig. 5 shows the influence stratification on the TIBL height. It shows that the TIBL height decreases as the stratification becomes strong.

The predicted values for the TIBL height from the four models were then compared with the experimental observations to determine which model, if any, gave the closest fit.

Plate's (1971) and Weisman's (1976) equations differ only by a constant. Each parameter in these two equations was directly measured in the experiments. Fig. 6(a) and (b) show the comparison of model predicted TIBL heights with the measurements in the water tank experiment. Both models underestimates the measured TIBL heights.

The model predictions by Raynor (1975) and Venkatram (1977) are plotted against the experimental observations in Fig. 6(c) and (d). Raynor model shows the best approximation to the observed TIBL height.

Two performance parameters listed in Table 1 for each of the equations compared to the laboratory data. The first is the bias, $\bar{d} = (1/n)\sum[P(i) - E(i)]$, where P(i) and E(i) represent the predicted and experimental values, respectively, for the i^{th} experiment and n is the total number of experiments. The second is the average absolute gross error, $|\bar{d}| = (1/n)\sum|P(i) - E(i)|$. The Raynor model clearly fits the experimental data best. It is proposed that the model proposed by Raynor would

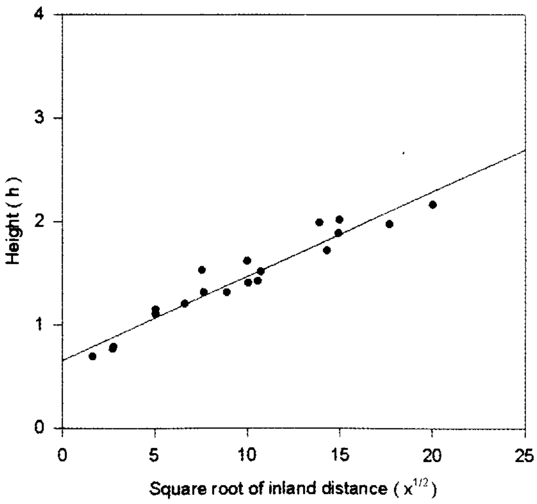

Fig. 4. The measured TIBL height along the square root of the inland distance.

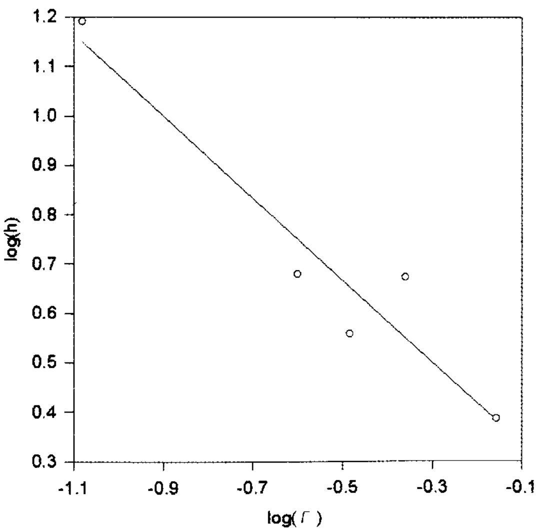

Fig. 5. The variation of TIBL height with the stratification.

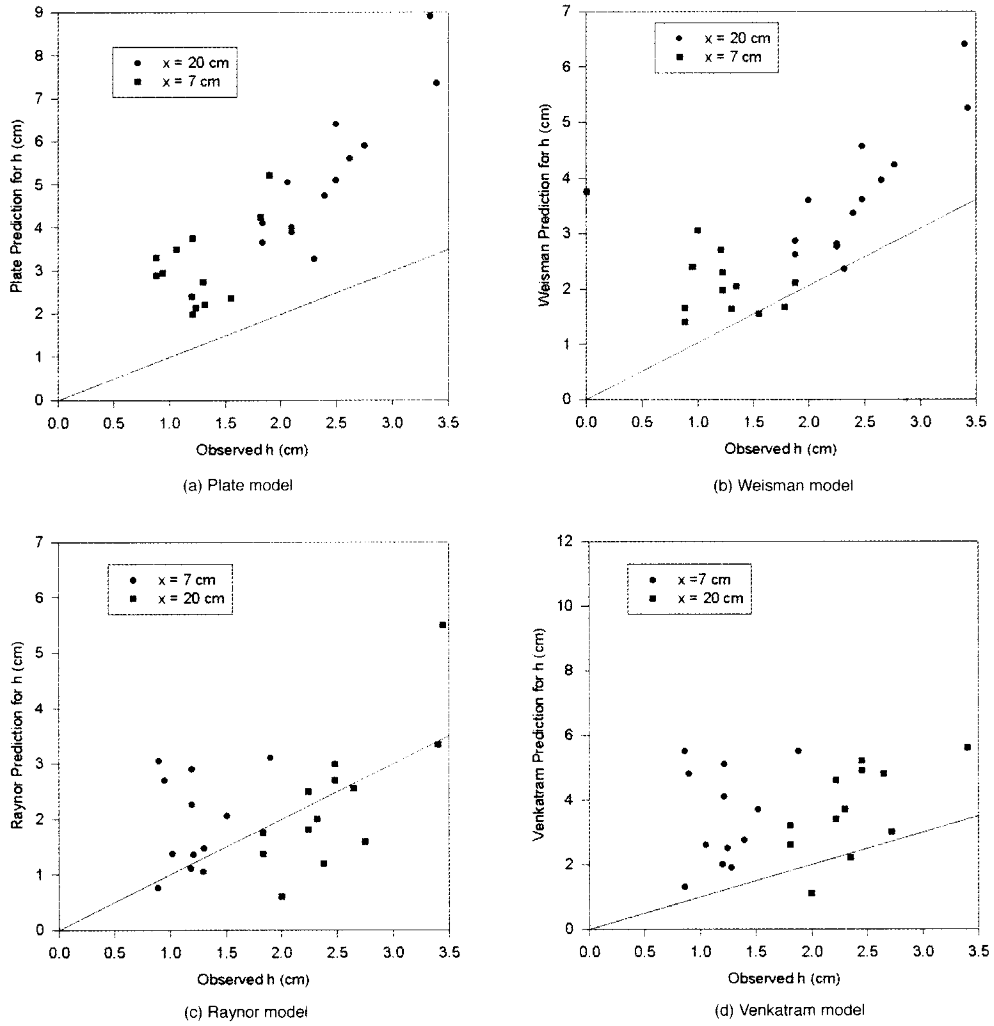

Fig. 6. Comparisons of the predicted h (x) by various models with the measurements.

Table 1. Comparison of performance parameters for model validation

Model	$\bar{d}$ cm	$\lvert\bar{d}\rvert$ cm
Plate	3.41	3.41
Raynor	0.47	0.86
Venkatram	2.36	2.47
Weisman	1.87	1.87

be used in the dispersion simulation of the fumigation near the coastal area.

5. CONCLUSIONS

In order to identify the best model to predict the TIBL height, the water tank experiment was carried out. The sea breeze and the TIBL were reproduced in the water tank. The height of TIBL depends on the heat flux from the ground, stratifications, and the intensity of the sea breeze. The measured heights of TIBL in the water tank were compared the predictions of the available models. The TIBL model by Raynor (1975) shows the best fit with the measurements and it would be used in the prediction of fumigation. Since this study is only focused to prove the validity of models for predicting TIBL height among the existing models in the literature, the application research is required to evaluate the fumigation from an elevated source with the selected TIBL model.

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