

Cross-Plane Particle Concentration Measurements in a Simulated Atmospheric Turbulent Boundary Layer

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ABSTRACT

We experimentally investigate turbulent particle dispersion in a neutral atmospheric boundary layer, with specific focus on ship exhaust plumes. The atmospheric boundary layer is simulated in a wind tunnel using a Counihan spire and barrier system. Particle concentration fields are obtained through an optical-based counting method calibrated with a particle counter. A scaled cruise ship model is tested at yaw angles of 0° , 45° , and 90° relative to the incoming wind. The results are compared with analytical solutions for point-source dispersion, including the classical point source in uniform-flow formulation and an extended solution for a point source in a boundary layer, obtained through a combination of analytical and numerical methods. Additional far-downstream measurements have been carried out to examine the generality of dispersion behavior.

1. Introduction

Ship emissions impact air quality, affecting human health and the environment, especially in coastal areas. Understanding the dispersion characteristics of pollutants is relevant for quantifying the impacts and potential control and regulation strategies.

Point source plume dispersion in turbulent boundary layer has been studied due to its generic interest in dispersion of hazardous materials and pollutants (Lim and Vanderwel, 2023). However, there are only few studies which focus on measuring both the velocity and concentration fields. Further, the ship and the exhaust add further complexities involving interaction between the exhaust jet and the incoming wind, as well as the wake effects (Correia et al., 2021).

Here, we model a neutral atmospheric boundary layer over sea/seashore conditions in wind tunnel and utilize it for dispersion study of ship exhaust. The goal is to develop simple models from the base case scenarios and also utilize the data for validation of numerical models. Preliminary results involved stream-wise measurements, which revealed some downwash effects (Sankaran et al.,

2024a). However, this does not capture the off-center motion of the plume, particularly when the ship is at a relative angle with respect to the incoming flow. In this study, we focus on the velocity fields at different cross plane downstream of the ship by stereoscopic PIV measurements (sPIV). Further, particle concentration fields are obtained through an optical-based counting method which is based on the same methodology as PIV measurements developed previously.

2. Experimental

The measurements were carried out in the atmospheric wind tunnel at the University of the Bundeswehr Munich. Counihan type spires and barrier system are utilized to mimic atmospheric boundary layer in the sea and shore conditions with neutral conditions (Robins, 1979).

The height of spire (H) utilized is 0.9 m. A generic cruise ship model (using a scale 1:1000) is positioned $9H$ downstream of the spire setup. The flow characteristics and Reynolds number independence of the flow characteristics are confirmed for the velocities studied by the sPIV measurements. The modelled boundary layer characteristics like the mean wind profile, turbulent intensities, roughness length, and integral length scale are quantified and compared with the expected conditions at marine conditions available (Hsu et al., 1994; VDI, 2000). The resultant velocity boundary layer exhibited power law profile with exponent $\alpha \sim 0.09$. This is in the range expected for sea/seashore conditions α between 0.08 and 0.12 (Hsu et al., 1994; VDI, 2000).

The experimental setup with the barrier and spires to simulate the atmospheric boundary layer in the wind tunnel, the placement of the ship model, and measurement cross plane are shown in figure 1.

Subsequently, experiments for concentration measurements with the exhaust flow were conducted. The exhaust flow is seeded with the flow tracers of DEHS particles with average diameter of $0.4 \mu\text{m}$. Here, we apply an optical-based particle counting method in conjunction with particle counter calibration to determine spatially resolved particle concentration measurements to evaluate the exhaust dispersion characteristics (Sankaran et al., 2024b).

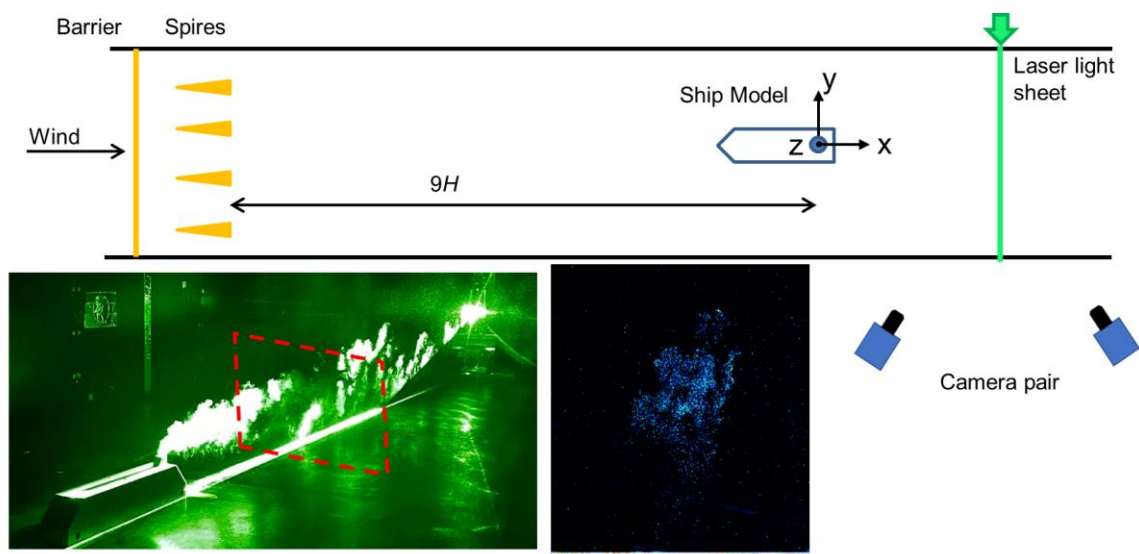


Figure 1. Top view of the experimental setup to measure the velocity and concentration field with the exhaust flow. The left inset shows the experimental snapshot with the visualized cross-plane (the plume is made visible by laser which is not used above). The middle inset shows the corrected image with the ship exhaust flow as seen from one of the camera.

3. Theory

Considering the classical turbulent diffusion analysis through an apparent turbulent diffusivity, the equation of diffusion assuming the boundary layer approximation is (Smith, 1957):

$$u(z) \frac{\partial C}{\partial x} = \frac{\partial}{\partial z} \left(K_z \frac{\partial C}{\partial z} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial C}{\partial y} \right) \quad (1)$$

where x is the streamwise direction, z is the wall normal direction. Here the turbulent diffusion in stream-wise direction is assumed small in comparison to advection.

The realistic scenario of the boundary layer is the power law profile of the mean flow as given below:

$$u(z) = u_0(z)^\alpha \quad (2)$$

An analytical solution for the above scenario with the following consideration for the dispersion coefficients has been solved by Smith (1957) for a ground level source, where the following diffusivity relations are assumed:

$$K_z = K_0(z)^{1-\alpha} \quad (3)$$

$$K_y = K_1(z)^{1-\alpha} \quad (4)$$

Here we follow similar steps as Smith (1957) and then solve for the elevated source numerically. Further one can compare the solution with the classical reflected Gaussian solution for the case when the flow is assumed as uniform. The analytical solution is given by (Stockie, 2011):

$$C(x, y, z) = \frac{Q}{4\pi x \sqrt{K_y K_z}} \exp\left(-\frac{u_0 y^2}{4K_y x}\right) \left[\exp\left(-\frac{u_0(z-h)^2}{4K_z x}\right) + \exp\left(-\frac{u_0(z+h)^2}{4K_z x}\right) \right] \quad (5)$$

Comparison of the experimental results and the theoretical consideration is discussed in the next section.

4. Results and Discussion

Figure 2 shows the average concentration field (the background concentration C_{inf} is deducted) normalized with respect to the exhaust concentration C_{ex} for different yaw angles of the ship studied. The concentration profiles reveal that the cross stream dispersion is higher than that to normal to the wall even for 0° case. This is attributed to the fact that the velocity fluctuations are higher along the span-wise in comparison to wall-normal direction for the boundary layer. The angling of the ship relative to the wind led to considerable downwash effect visible from the

concentration peak near the surface and the broadened concentration profile close to the surface. The plume is also displaced with respect to the exhaust axis due to the non-symmetrical effect of the separation around the ship.

The theoretical prediction by the uniform flow and the boundary layer effect considered is presented in figure 3. The boundary layer consideration does over-predict the peak of the concentration. Further, there is considerable difference in the shape of the concentration profile. It needs to be noted that the dispersion coefficients are used as fit here and future efforts need to be aimed to directly calculate the dispersion coefficients from simultaneous velocity and concentration measurements.

Figure 4 presents the normalized concentration fields measured at a downstream distance of 27L from the exhaust location. At this distance, the plume has undergone substantial turbulent mixing within the atmospheric boundary layer, resulting in a significantly broader concentration distribution compared to the near-field measurements shown in figure 2. needs to be noted that exhaust velocity is considerably higher in comparison to that of figure 2. Still, there is lateral displacement of the plume observed in case of 45° case, while the other two cases nearly show similar profile.

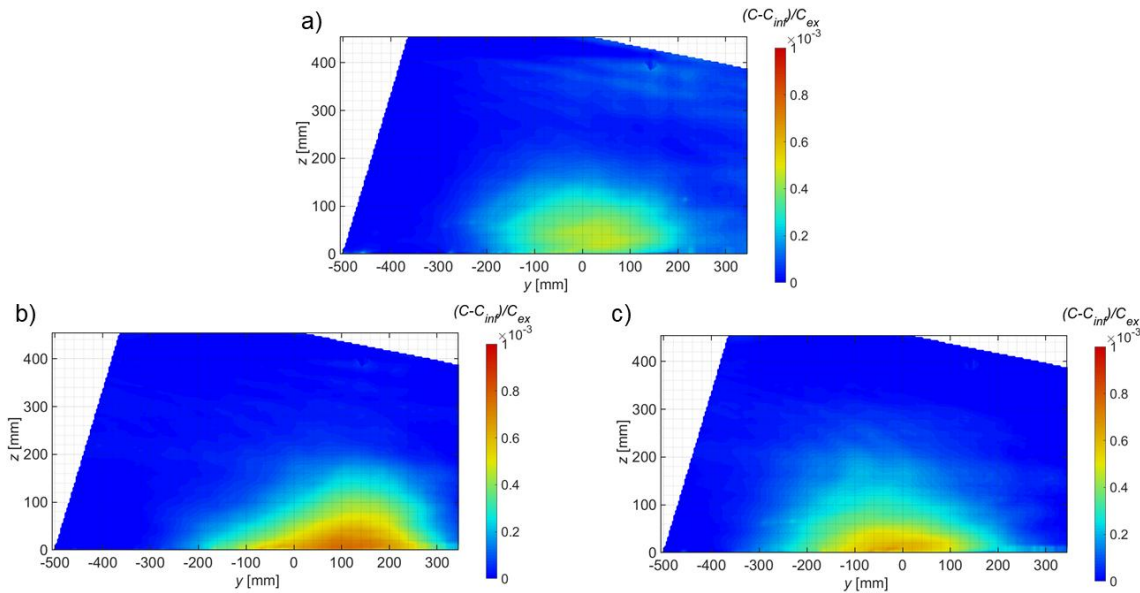


Figure 2. The average normalized concentration field (2000 snapshots) at a cross plane $6.6 \times L$ from the exhaust with 8 m/s velocity at $z = 300$ mm and 16 m/s average exhaust velocity (exhaust flow rate = 12 lpm) at different ship yaw angle: (a) 0°, (b) 45° and (c) 90°. The center of the exhaust is located at $y = 0$ mm, $z = 50$ mm.

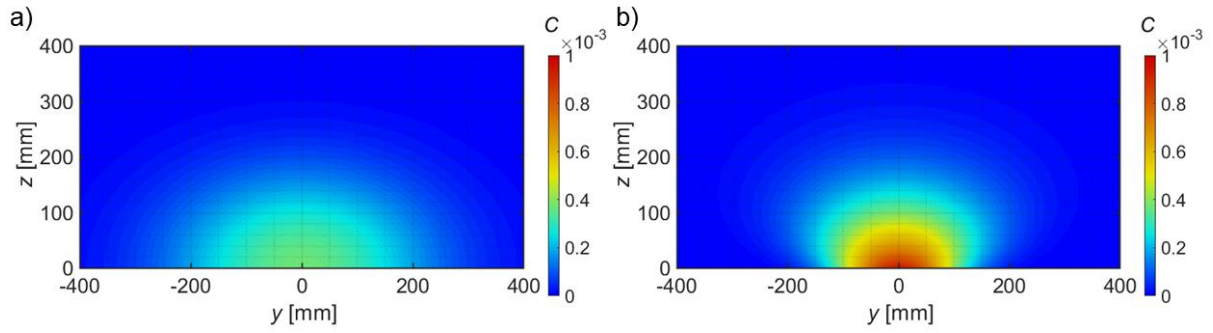


Figure 3. Theoretical average normalized concentration field with 12 lpm exhaust flow rate: (a) the analytical solution from equation 5; (b) Part analytical – part numerical solution utilizing equations 1-4. Here, the following average values are considered: $K_z = 0.03 \text{ m}^2/\text{s}$, $K_y = 0.07 \text{ m}^2/\text{s}$, $\alpha = 0.1$, exhaust flow rate = 12 lpm, effective height of source = 60 mm.

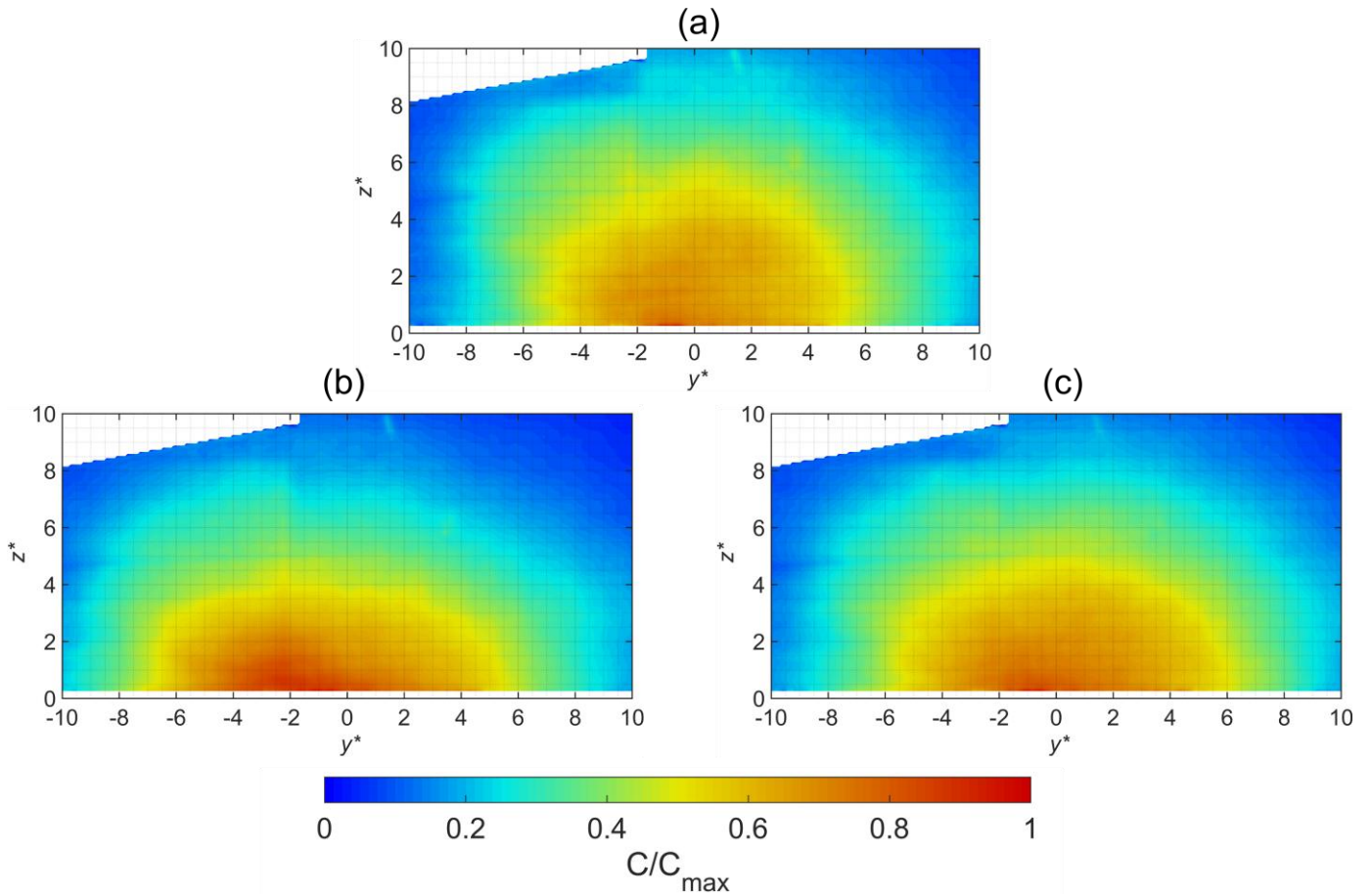


Figure 4. The average normalized concentration field (2000 snapshots) at a cross plane $27 \times L$ from the exhaust with 8 m/s velocity at $z = 300 \text{ mm}$ and 50 m/s average exhaust velocity (exhaust flow rate = 38 lpm) at different ship yaw angle: (a) 0° , (b) 45° and (c) 90° . The coordinates are non-dimensionalized by the exhaust height of 50 mm and the concentration by the maximum for each case.

5. Conclusions

This study investigates turbulent dispersion of ship exhaust plumes in a neutral atmospheric boundary layer using wind tunnel experiments. The particle image based concentration method was successfully applied to derive concentration distribution downstream of the ship exhaust. The effect of yaw angle on the dispersion characteristics on different cross planes is investigated. The results revealed the significant downward dispersion for angled cases.

Experimental results were compared with classical Gaussian point-source dispersion in uniform flow and an extended solution accounting for boundary layer velocity profiles. The boundary layer solution reproduced plume structure but over-predicted concentration peaks. Far-downstream measurements showed that the angled case specifically 45°. shows lateral displacement of the plume even at 27L.

Acknowledgments

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