Experimental Investigation of Air-Sea Transfer of Momentum and Enthalpy at High Wind Speed

By: Moshe Alamaro [1], Kerry Emanuel [2] and Jeffrey Colton
Massachusetts Institute of Technology, Cambridge, MA 02139

Wade McGillis and James Edson
Woods Hole Oceanographic Institution, Woods Hole, MA 02543

1. Introduction

Thermodynamic analysis and numerical modeling of hurricane intensity has shown that it is sensitive to momentum and enthalpy transfer from the ocean surface. Direct measurements of drag, evaporation, and sensible heat transfer are not easily performed on the high seas. Therefore, a wind wave tank has been constructed in which a few aspects of a tropical storm boundary layer are simulated (Alamaro, 2001). The air velocity inside the annular tank is comparable to that of a hurricane.

The design of the wind wave tank and the initial experiments create a foundation for future and more comprehensive experimental studies. This paper outlines the design of the tank and the hydrodynamics of the rotational flow, using angular momentum analysis. Experimental data on drag at high wind speeds obtained using spindown experiments is also provided.

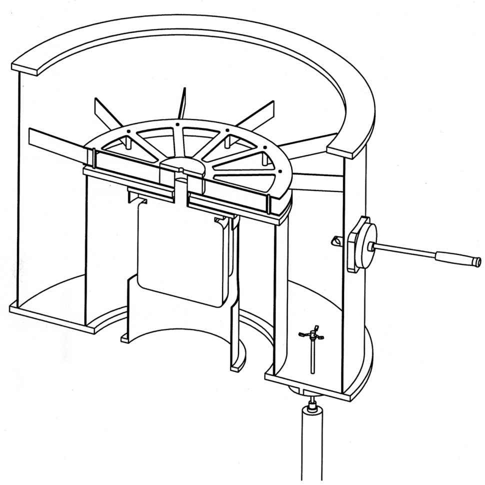

Fig. 1: Annular wind wave tank

2. Experimental Apparatus

A circular wind wave tank made of two acrylic concentric walls has been constructed, as shown in Fig. 1. The outer and inner radiuses are $r_0 = 0.479\ m$ and $r_{in} = 0.284\ m$ respectively. The water height can be varied in the annulus. A paddle powered by an electric motor moves the air over the water surface at velocities comparable to that of a hurricane.

The shear stress over the water surface accelerates the water whose velocity is measured by an Acoustic Doppler Velocitmeter (ADV). An anemometer measures the air velocity. The tank is equipped with an adjustable false bottom that enables the use of different distances from the paddle to the water surface for the same amount of water. The tank is also equipped for enthalpy transfer experiments although this paper provides results for momentum transfer and drag coefficient experiments only.

3. Spindown experiments

The spindown technique is central to this investigation. It provides information on the deceleration of the water mass that, in turn, enables the calculation of the shear stress over the water surface owing to the airflow. The procedure for the spindown is the following:

a. Bring the water to steady state rigid body rotation under a certain V_s - the relative air velocity over the moving water surface.

b. Cut the power to the electric motor.

Measuring $\frac{\partial\Omega}{\partial t} = \frac{1}{R}\frac{\partial V_w}{\partial t}$ where R is the distance of the ADV from the tank center and V_w is the water velocity over the ADV enables the calculation of the shear stress via:

$$\tau_s = \frac{3}{4}\rho_w H \frac{\left(r_0^4 - r_{in}^4\right)}{\left(r_0^3 - r_{in}^3\right)}\frac{\partial\Omega}{\partial t} \quad (1)$$

where H is the water depth, ρ_w is the water density and Ω is the angular velocity of the water mass, which is approximated as being in rigid body rotation.

The water motion during the spindown in the annulus is hypothesized to be a channel flow. The Reynolds number R_e of this turbulent flow is on the order of 10^5.

Email addresses
1. alamaro@mit.edu
2. emanuel@texmex.mit.edu

The equation describing the water motion during the spindown is:

$$\frac{\partial V_w}{\partial t} = -A\rho_w C_{DW}(R_e)V_w^2 = -k_1 C_{DW}(R_e)V_w^2 \qquad (2)$$

where A is the wet wall area, k_1 is some constant for a specific experiment, C_{DW} is the drag coefficient for the water motion and is a power function of the Reynolds number or equivalently, a power function of the water velocity. Solving (2), it can be shown that:

$$V_w(t) = \frac{V_m}{(1+k\cdot t)^n} \qquad n>1 \qquad (3)$$

Where V_m is the water velocity at $t=0$, the start of the spindown. k and n are constants that are obtained by fitting.

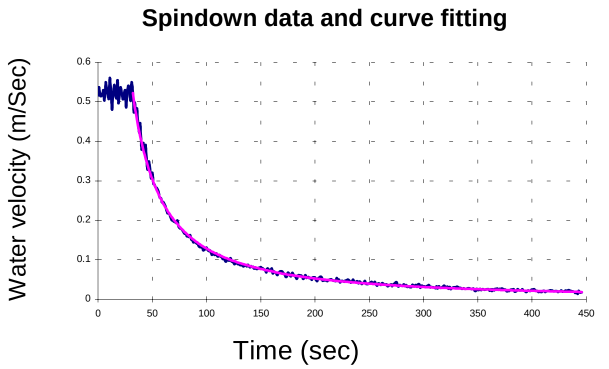

Fig. 3: Typical spindown experiment and fitting that provides n and k for equation (3).

The derivative of eq. (3) gives:

$$\frac{\partial V_w}{\partial t} = \frac{-nkV_m}{(1+k\cdot t)^{n+1}} = \frac{-nkV_w}{(1+k\cdot t)} = -nkV_w\left(\frac{V_m}{V_w}\right)^{\frac{1}{n}} \qquad (4)$$

The water velocity V_w in the steady state is measured for various RPM or air velocity. For each spindown experiment, once n and k are determined, for each air velocity there is a corresponding water velocity that enables substituting the expression given in (4) into eq. (1) and the shear stress as a function of the air velocity can be calculated.

4. Results

Given the shear stress as a function of relative air velocity, the friction velocity u_* is determined. This enables the "roughness" of the water surface to be calculated using:

$$\frac{u_a}{u_*} = \frac{1}{k}\ln\left(\frac{z_a}{z_0}\right) \qquad (5)$$

where u_a is the measured air velocity at a height z_a above the water surface, $k=0.41$, and z_0 is the roughness. The velocity at a height of 10 m is obtained by $U_{10} = \frac{u_*}{k}\ln\left(\frac{10}{z_0}\right)$ and finally the drag coefficient is:

$$C_D = \frac{\tau_s}{\rho_a U_{10}^2} = \left(\frac{u_*}{U_{10}}\right)^2 \qquad (6)$$

Results are presented in Fig. 4.

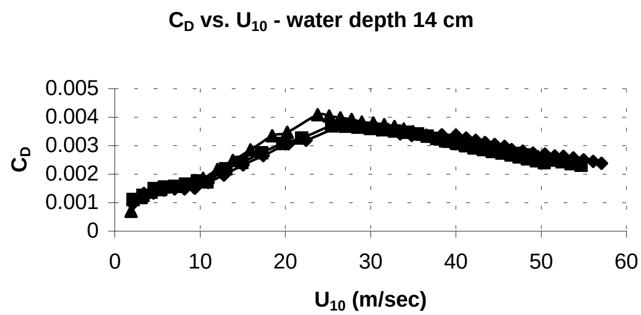

Fig. 4: Drag coefficient vs. U_{10} for various elevation of false bottom.

It is observed that at a paddle RPM that corresponds to $U_{10} \cong 25\ m/\mathbf{sec}$ and higher, water spray is generated. It is estimated that the centrifugal acceleration on the spray is on the order of $100-200\ m/\mathbf{sec}^2$ so its flight time scale before being splashed onto the tank walls is about $\tau \approx 0.1\ \mathbf{sec}$. This point may explain the declining C_D for $U_{10} > 25\ m/\mathbf{sec}$ and is the subject of further investigation.

A complete manuscript of this work can be found in the reference and the website below.

5. Reference

Alamaro, M.: "Wind wave tank for experimental investigation of momentum and enthalpy transfer from the ocean surface at high wind speed", M.S. Thesis, MIT, May 2001. PDF file website address:

http://web.mit.edu/hurricanelab/ThesisWebsite.pdf