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A random synthetic jet array driven turbulence tank

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Abstract We measure the flow above an array of randomly driven, upward-facing synthetic jets used to generate turbulence beneath a free surface. Compared to grid stirred tanks (GSTs), this system offers smaller mean flows at equivalent turbulent Reynolds numbers with fewer moving parts.

1 Introduction

The grid stirred tank (GST) is the standard facility for studying turbulence in the absence of advection (DeSilva and Fernando 1994; Brumley and Jirka 1987). All GSTs, however, are susceptible to secondary flows from several sources (Fernando and DeSilva 1993). Due to its highly mechanical nature, a GST exhibits irregularities in the drive motor, multiple drive shafts that are difficult to align (or grid wobble if there is only one shaft), and departure from pure grid geometry where the drive shaft(s) meet the grid. The GST boundary conditions suffer due to a finite gap between grid edges and the wall. Furthermore, many designs have surface-piercing elements that can impede measurements at the free surface. The deterministic nature of the grid motion can permit secondary flows, once established, to persist in a dynamic equilibrium.

Researchers working over the past 30 years with several different facilities typically report that secondary flows are present but negligible. We consider the ratio $\bar{u}/u_{\mathrm{rms}}$, where $u=\bar{u}+u'$, $u_{\mathrm{rms}}=\sqrt{\overline{u'^2}}$, and $(\bar{\ })$ indicates the time-average linear operator. Reported and inferred values from a variety of GST experiments (Table 1) show that $\bar{u}/u_{\mathrm{rms}}$ is typically about 0.25, with a best case value of 0.10 in a single-coordinate direction. In the worst case, $\bar{u}/u_{\mathrm{rms}}$ can exceed 1. Whether it is fair to neglect secondary flows of this magnitude depends on the purpose of each experiment; in our case, the removal of advective transport will greatly increase the accuracy of our intended measurements of the turbulent transport of CO_2 across an air–gas interface, as in Chu and Jirka (1992).

2 Apparatus

We propose a new means of generating turbulence beneath an undisturbed free surface, inspired by the extremely successful active wind tunnel grid of Mydlarski and Warhaft (1996). It resembles the synthetic jet-generated turbulence facilities of Hwang and Eaton (2004) and Birouk (2003). We envision an array of vertically oriented synthetic jets[1], each switching on and off randomly, generating turbulence from below with minimal disruption of the free surface. The synthetic jets will merge as do the grid wakes in a GST, and initial anisotropy from the jets will be erased by the turbulent stirring as distance from the orifice plane increases (Villermaux and Hopfinger 1994). Random forcing will prevent most sources of secondary flow, and will greatly decrease the opportunity for secondary flows to persist if established. By adjusting the parameters of the random forcing, we can select a range of frequencies at which to drive the tank, essentially choosing the integral length scale and low wave number region of the power spectrum.

We have retrofitted an existing facility to approximate such a random jet array, and the results are quite encouraging. We have nine synthetic jets arranged in a square lattice at the bottom of a rectangular tank (10.8 cm×10.8 cm×40 cm). As seen in Fig. 1, the incurrent ports are spatially adjacent to excurrent ports (all ports are 0.9 cm in diameter). The excurrent ports obey reflective symmetry with the walls, as suggested by Fernando and DeSilva (1993). One centrifugal pump drives all jets, which

[1] We define synthetic jets in the broadest sense, such that the net mass flux, integrated over either space or time, is zero for each synthetic jet, i.e., an incurrent and excurrent port coupled via a pump or a single port that oscillates in time between incurrent and excurrent flows.

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Table 1. Reported GST and random jet array secondary flow ratios. All values are ensemble-averaged over time as well as over the spatial dimensions indicated. The grid Reynolds number, Re_{grid}, is commonly written in terms of GST operating parameters, but is also twice the turbulent Reynolds number, $Re=u_{rms}L/v$, where L is the integral length scale. The final data point is for two facing non-random synthetic jet arrays. Data for Re_{grid}=327 was taken in our GST, the same one used in Brumley and Jirka (1987) and Chu and Jirka (1992), with the same ADV and methodology used in our measurements

Re_{grid}	$\bar{u}/u_{rms}$	$\bar{v}/v_{rms}$	$\bar{w}/w_{rms}$	Averaged over	Reference
50	0.42	n/a	0.59	*x, y*	McDougall (1979)
85	0.43	n/a	n/a	*z*	Thompson and Turner (1994)
100±50	0.10	n/a	n/a	Single point	Fernando and DeSilva (1993)
234	0.17	0.25	0.17	*x, y*	McKenna (2000)
240	0.05	0.15	0.04	Single point	This study
240	0.08	0.07	0.36	*x, y, z*	This study
282	0.17	0.07	0.50	*x, y*	McKenna (2000)
327	0.28	0.07	1.11	*x*	see caption
349	0.04	0.20	0.50	*x, y*	McKenna (2000)
360	0.05	0.06	0.28	*x, y, z*	This study
411	0.07	0.04	0.33	*x, y*	McKenna (2000)
469	0.20	0.04	0.33	*x, y*	McKenna (2000)
530	0.25	0.17	0.33	*x, y*	McKenna (2000)
596	0.14	0.17	0.08	*x, y*	McKenna (2000)
665	0.25	0.13	0.25	*x, y*	McKenna (2000)
730	0.50	0.20	0.50	*x, y*	McKenna (2000)
789	0.50	0.17	1.00	*x, y*	McKenna (2000)
898	0.50	0.13	0.50	*x, y*	McKenna (2000)
974	0.50	0.17	1.00	*x, y*	McKenna (2000)
1,200	0.20	n/a	0.37	*x, y, z*	Bourdel (2000)

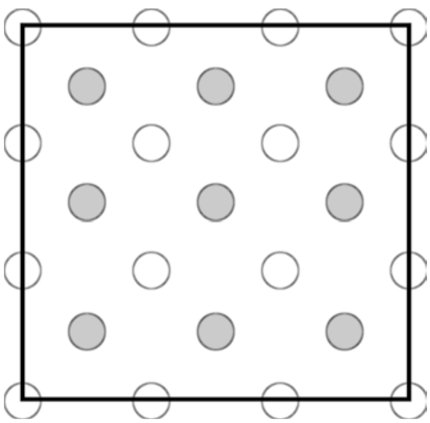

Fig. 1. Orifice plane of the random synthetic jet array. The *shaded circles* are excurrent ports (i.e., flow into the tank), *empty circles* are incurrent ports, and *lines* show the tank's inner walls (tank is 10.8 cm×10.8 cm)

are then turned on and off by solenoid valves (Farmington Engineering). By varying the pump speed, we can adjust U_J, the jet exit velocity. The following algorithm is used to randomize each jet independently: Each jet turns on for a time T_i, chosen from a normal distribution with mean μ and variance σ^2. When T_i has elapsed, that jet turns off for a time ,T_o, chosen from the same distribution; we then choose a new value for T_i and so on.

3 Results

The resulting flow is turbulent, with $R_\lambda \approx 30$–50[2]. Velocity measurements were collected at 25 Hz for 3–10 min with a three-component Sontek ADV 10 MHz LAB, at several points in x, y, and z, while independently varying U_J, μ, σ, and Z_c, or "cover" (the height of the free surface above the orifice plane). Averaging over all of these runs (and over results for u, v, and w), the mean value of $\bar{u}/u_{rms}$ is 0.16. The same quantity, computed from the historical GST data in Table 1, is 0.34. Similarly, the median values are 0.09 and 0.25 for our random jet array and the GSTs, respectively. Bootstrap analysis shows that this superior performance of the random jet array is significant at the 95% confidence level (Efron and Tibshirani 1993).

A typical example of the velocity ratio is shown in Table 1 for μ=0.5 s, σ=0.15 s, U_J=50 cm/s, Z_c=36 cm, **x**=(1 cm, 1 cm, 24 cm), where the origin is in the center of the orifice plane. Also shown in Table 1 are results averaged over μ, σ, **x**, and Z_c at a given Re[3]. We observe that $\bar{w}$ is consistently the largest mean; this was also observed by McKenna and McGillis (2000) in their GST. Based on the data in Table 1, the ratio $\bar{w}/w_{rms}$ is still significantly less in our facility than in GSTs (at the 95% confidence level in the mean, and the 90% confidence level in the median).

Also in agreement with previous GST results is the isotropy of the rms turbulent velocities produced by the random jet array. Median values over all our datasets give u_{rms}/v_{rms}=0.95, u_{rms}/w_{rms}=1.19, and v_{rms}/w_{rms}=1.23. For GSTs, u_{rms}/w_{rms} has been consistently reported as 1.1 (Hopfinger and Toly 1976; McKenna and McGillis 2000).

We do not find a statistically significant difference due to varying position, Z_c, μ, or σ/μ. However, tests run with and without reflective symmetry at the walls show that fulfilling this boundary condition provides a statistically significant reduction in secondary flows.

The success of the random jet array is quite encouraging, especially given the crude nature of the prototype facility. A full-fledged facility should perform much better than this simple mock-up. A wider range of spatial scales would be accessible in a system with more jets. We expect

[2] Because we cannot use Taylor's frozen field hypothesis in facilities of this nature, Re_λ and Re are estimated from spatial data in PIV measurements made in a previous generation of the facility. PIV was taken in a 2 cm×2 cm plane with 0.1-mm resolution. From the velocity field in x and z, we can find the autocorrelation functions, which we then integrate to obtain $L\approx0.3$ cm. We find ϵ from local gradients and by fitting to power spectra (Cowen and Monismith 1997; Liao and Cowen 2002).

[3] We find that u_{rms} is proportional to U_J; thus, Re is proportional to U_J.

64 jets to be an ideal number, balancing excellent spatial resolution with ease of control. Each jet should be run by an individual pump, because, in driving our prototype system with a single pump, we find that U_J varies, depending on how many jets are on at a given moment. Because our system has no moving parts, and because of jets' *Re*-independent features, it should be possible to upscale the apparatus to significantly larger Reynolds numbers.

In conclusion, we have demonstrated that an active synthetic jet array can yield high levels of turbulence with very low mean flow. The mean flows are consistently smaller than both GSTs and passive synthetic jet arrays.

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