

Fragmentation in turbulence revisited – Design of a homogeneous isotropic turbulence experiment for droplet breakup

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ABSTRACT

The present study gives an overview on the preliminary experiments and design of a test rig for sustained homogeneous isotropic turbulence (HIT) with zero mean flow to study turbulent fragmentation of droplets in liquid-liquid flows of similar density. The design follows the concept of randomly actuated synthetic jet arrays (RASJA) to generate a region of HIT that extends several integral length scales. For the fragmentation of bubbles and droplets, the injected initial size needs to be larger than the Kolmogorov-Hinze scale. Hence, there are additional constraints for multiphase experiments in HIT that we discuss, including the initial droplet generation and characteristic time-scales involved in the turbulent fragmentation. The latter entails experimental quantification of the turbulence decay time-scale with distance from the jet arrays, as well as the residence time of the dispersed phase in the HIT region to ensure a sustained fragmentation cascade.

1. Introduction

In numerical studies, homogeneous isotropic turbulence is a relatively-straightforward concept to employ in studying various aspects of single-phase or multiphase turbulence in a well-defined, canonical flow configuration. However, experimentally generating HIT with sufficient quality with respect to isotropy, zero mean flow and sustainability in a region that covers several integral length scales in size remains somewhat challenging. Since the seminal work of Variano & Cowen (2008) multiple researchers have adopted their concept of randomly actuated synthetic jet arrays, as such jet arrays provide a good compromise to achieve a proper flow characteristics. While in their original work Variano & Cowen (2008) used a single-sided jet array, many experimental setups have been extended to two facing jet arrays (Bellani & Variano, 2013; Byron et al., 2019; Esteban et al., 2019; Ruth & Coletti, 2024), four opposing jet arrays in an octagonal tank (Bang & Pujara, 2023) or jet arrays pointing toward the center of the test region from multiple directions (McCutchan & Johnson, 2023). In the present study we are addressing various aspects to design

an experimental setup to investigate droplet fragmentation in a region of HIT and observe multiple breakup cycles until the droplet size distribution is in the range below the Kolmogorov-Hinze (K-H) scale (Hinze, 1955). In contrast to single-phase turbulence studies additional considerations need to be taken to ensure that the local dissipation rate is large enough to break bubbles or droplets in the turbulent flow of the bulk medium. Some researchers apply a lower number of permanent jets to provide high dissipation rates to investigate bubble (Ruth et al., 2022) or droplet fragmentation (Beckedorff et al., 2025). As a consequence, the turbulent region is either not homogeneous, not isotropic or has only a small extent. Hence, there are a number of tradeoffs for multiphase problems in HIT. For the experiments discussed herein, we decided to stick with the RASJA concept, increase the kinetic energy to ensure high dissipation rates, and inject droplets of sufficiently large size to observe a cascade of fragmentation events for the available level of turbulence. Following our previous study based on the direct numerical simulation (Saeedipour & Schneiderbauer, 2025), the experimental characterization of vorticity and enstrophy dynamics in the HIT region is essential for the outcome of the fragmentation cascade in turbulent emulsification.

2. Design of the experimental apparatus

The general design of our test facility follows the design of other installations to generate HIT using two opposing jet arrays (Fig. 1). The jets are operated by low-cost bilge pumps arranged in a regular grid of 110×110 mm. The "sunbathing" algorithm proposed by Variano & Cowen (2008) is used to operate the jets randomly. We chose the strongest bilge pumps available (1100 gph) delivering a flow rate of up to 1.16 liter/s resulting in jet Reynolds numbers of 6.65×10^4 when operated at full power. The distance between the two jet arrays is variable, as is the power of the pumps, which is modulated by pulse width modulation (PWM). Hence, we have multiple degrees of freedom to adjust the dissipation rate of the turbulence in the central region of HIT.

During the operation of the jet arrays, it is impossible to judge if a pump that is supposed to be active does indeed produce a jet. Hence, we see a need to have a feedback loop telling the actual power consumption of each PWM channel to identify broken pumps. To control each pump, we chose PWM modules controlled via a CAN bus (Controller Area Network). This type of module (Sabo PLM730) provides eight output channels and is able to measure the power consumption on each channel. The CAN bus is controlled via a USB interface (Kvaser Leaf Light v2) and the entire program to operate the test rig is implemented in Python. When switching on the system, a self-test is run to check every pump for correct operation. Since the CAN bus is very fast on data communication, this self-test can be run in less than 60s for all of the 128 pumps. We consider this approach important to ensure reliable operation and reproducibility of experiments.

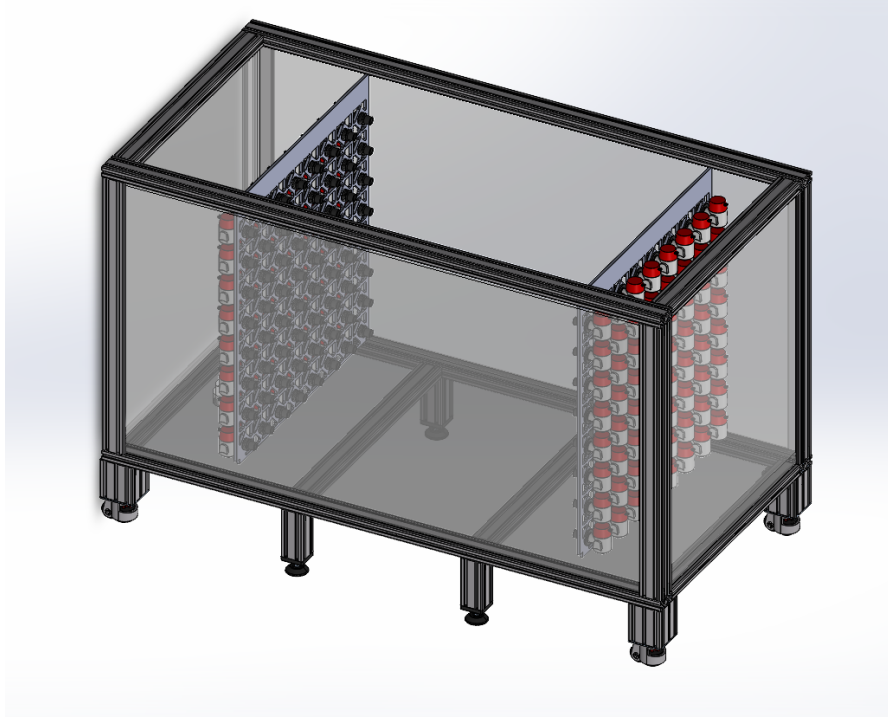


Figure 1. Sketch of the experimental setup with two opposing jet arrays driven by 2 x 8 x 8 bilge pumps.

3. Considerations about bubble and droplet breakup

To be able to observe multiple breakup cycles, the initial size of the inserted bubbles or droplets needs to be larger than the K-H scale

$$d_{KH} = \left(\frac{We_c \sigma_{DB}}{2 \rho_B} \right)^{3/5} \varepsilon^{-2/5} \quad (1)$$

calculated with the critical Weber number $We_c = 1.17$, the interfacial tension σ_{DB} between the dispersed material and the bulk medium, the density of the bulk fluid ρ_B , and the turbulent dissipation rate ε . With the dissipation rates reported in literature, we can estimate d_H for certain values of ε . Figure 2 shows the resulting K-H scale for air bubbles (blue line) and oil droplets (red line).

It is apparent that the asymptotic behavior does not drastically reduce the Hinze scale above dissipation rates $\varepsilon > 2 \cdot 10^{-3} \text{ m}^2 \text{ s}^{-3}$. As a consequence, the initial droplet or bubble size needs to be well above 20 mm. Since it is difficult to generate objects of this size via needle injection, a practical solution to this problem is the use of a rotating cup device (Landel et al., 2008). Figure 3 shows such a device that is submersible and can release large bubbles or droplets after accumulating a defined volume of air or oil, respectively. For oil droplets we observe a wetting effect in the preliminary experiments that causes a strong droplet tail, however, we believe that this can be eliminated by improving the surface quality of the cup.

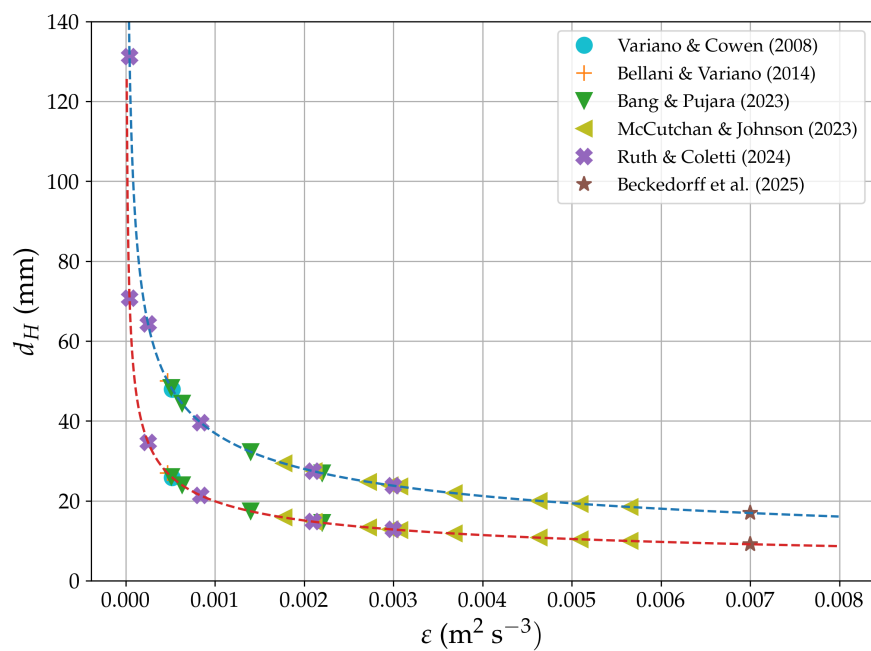


Figure 2. K-H scale resulting from the dissipation rates documented in the references calculated for air (blue dashed line) and vegetable oil (red dashed line).

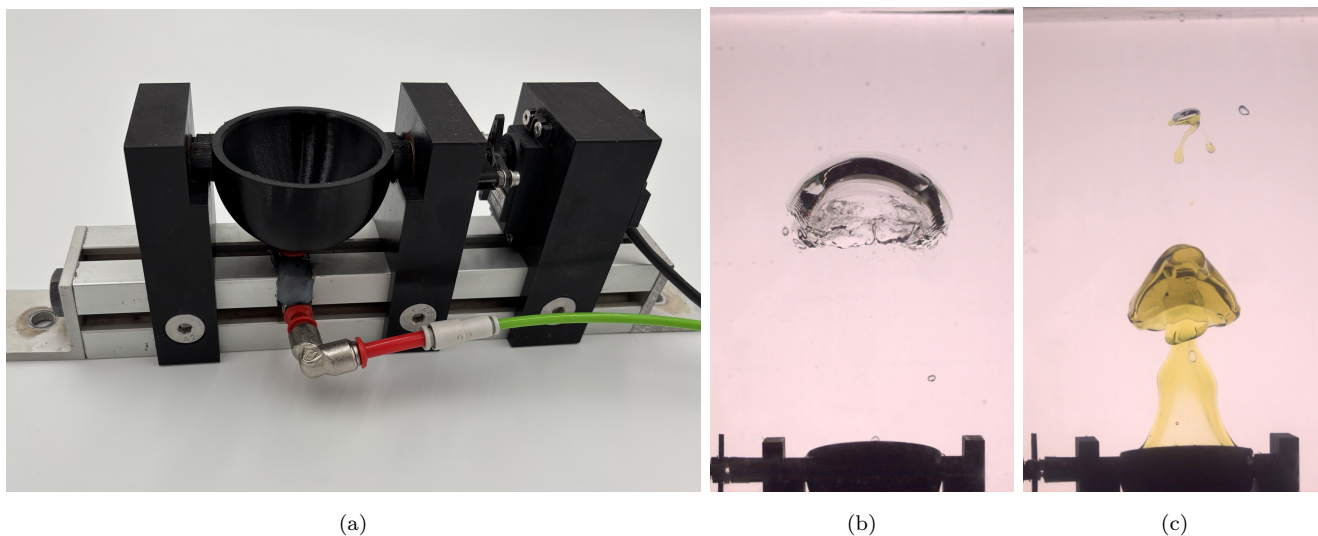


Figure 3. Rotating cup device (a) to release air bubbles (b) and oil droplets (c) much larger than the Hinze scale. The oil shows a strong wetting behavior in the cup that needs to be improved by coating.

4. Experimental results

4.1. Single jet experiments

Before building the 2 m^3 basin shown in Fig. 1, we conducted tests with a single pump to measure the characteristics of a single jet. The tank used has a square cross section of $0.5 \times 0.5\text{ m}^2$ and a height of 2 m . For the single jet tests an additional 3D-printed flow straightener was attached to the pump outlet to avoid jet deflection. Rotary pumps inherently produce some swirl structure and the jet would deviate from its central axis with increasing distance to the nozzle outlet. The resistance of this additional flow straightener reduced the jet Reynolds number to $\text{Re}=4.75 \times 10^4$. A standard 2D PIV setup was used to analyze the flow field in the center of the jet up to a distance of 750 mm . Based on flow field data, the turbulent kinetic energy (TKE) and its dissipation rate ε have been calculated under the assumption of local axisymmetric turbulence (George & Hussein, 1991):

$$\varepsilon = \nu \left[-\langle \overline{s_{11}^2} \rangle + 2 \langle \overline{s_{12}^2} \rangle + 2 \langle \overline{s_{21}^2} \rangle + 8 \langle \overline{s_{22}^2} \rangle \right] \quad (2)$$

with s_{ij} as the fluctuating strain rates. As expected, both TKE and ε drop rapidly with increasing distance to the jet outlet (Fig. 4a). For distances to the jet outlet $y/D > 35$, we observe dissipation rates in the range $10^{-3} < \varepsilon < 10^{-2}\text{ m}^2\text{s}^{-3}$, which is in the desired range for the K-H scale with respect to Fig. 2.

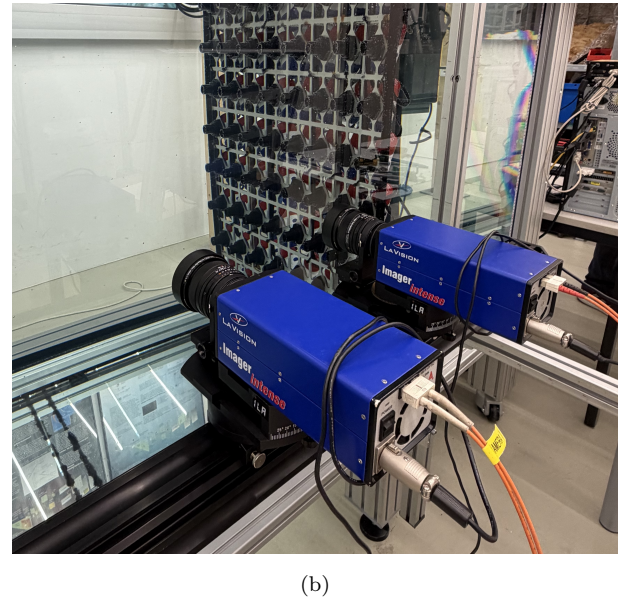
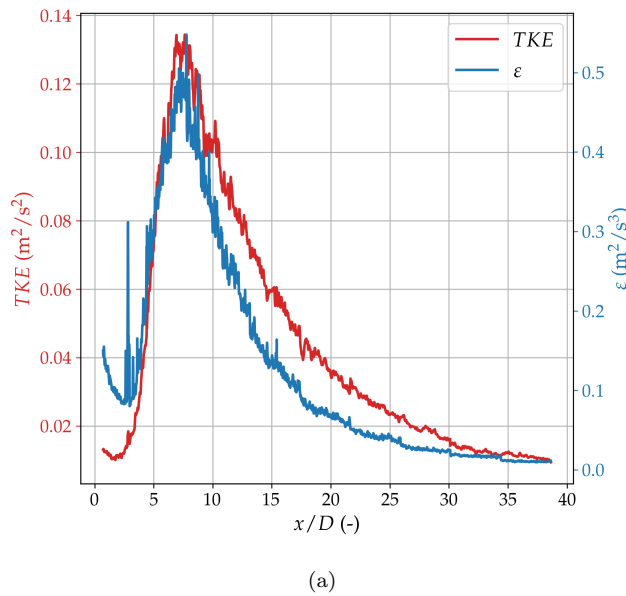


Figure 4. (a) Preliminary data from a single pump measurement showing turbulent kinetic energy and turbulent dissipation rate averaged on the center axis of the vertical jet of $\text{Re}=4.75 \times 10^4$. (b) 2D PIV setup with single-sided pump array.

4.2. Single-sided pump array

One of the two pump arrays have been finished meanwhile and commissioning tests are ongoing to classify turbulence characteristics. The first tests have been conducted using 2D PIV (Fig. 4b). The recorded region of interest covers a horizontal distance to the pump outlet of 580 to 800 mm corresponding to the lower right corner of Fig. 4a. This distance range represents a typical scenario for experiments in the central region of two pump arrays. For these tests the laser light sheet was positioned in alignment with one vertical line of pumps and not exactly in the center of the tank. The data for TKE and ε in Fig. 5a are in good agreement with the single jet results of Fig. 4a. The fact that the measurement plane is not located between the pump arrays results in a small residual mean flow in the horizontal direction and while the distribution of vertical velocity fluctuations v' perfectly follows a normal distribution, the horizontal fluctuations u' shows a skewed distribution in the direction of the jets. We expect this effect to vanish when moving the measurement plane and adding the second pump array to the tank. Most importantly, the turbulent dissipation rate ε remains in the desired range and is also expected to increase when using the full set of randomly actuated pumps. To get an impression of the random flow field Fig. 6 depicts the out-of-plane vorticity of an instantaneous snapshot.

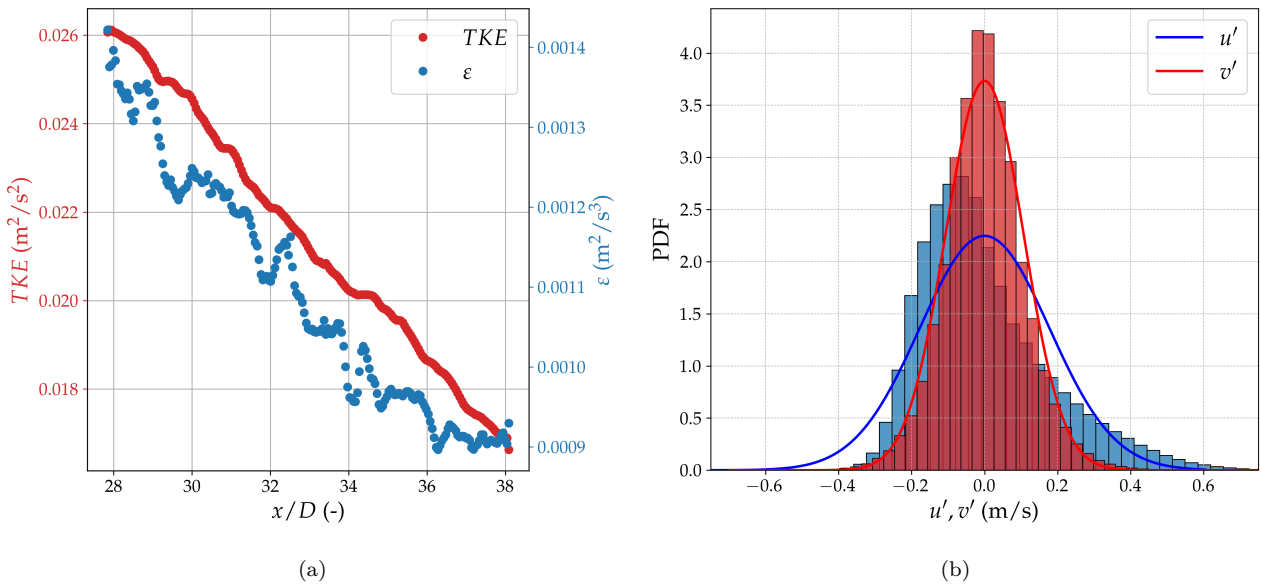


Figure 5. (a) 2D PIV measurements of turbulence characteristics on one-sided pump array within the region $580 < x < 800$ mm from the array. (b) PDF of horizontal and vertical velocity fluctuations u' and v' in the same downstream region. The solid lines indicate the best normal distribution fit. While v' follows a normal distribution, u' shows asymmetric behavior when using only a single-sided pump array.

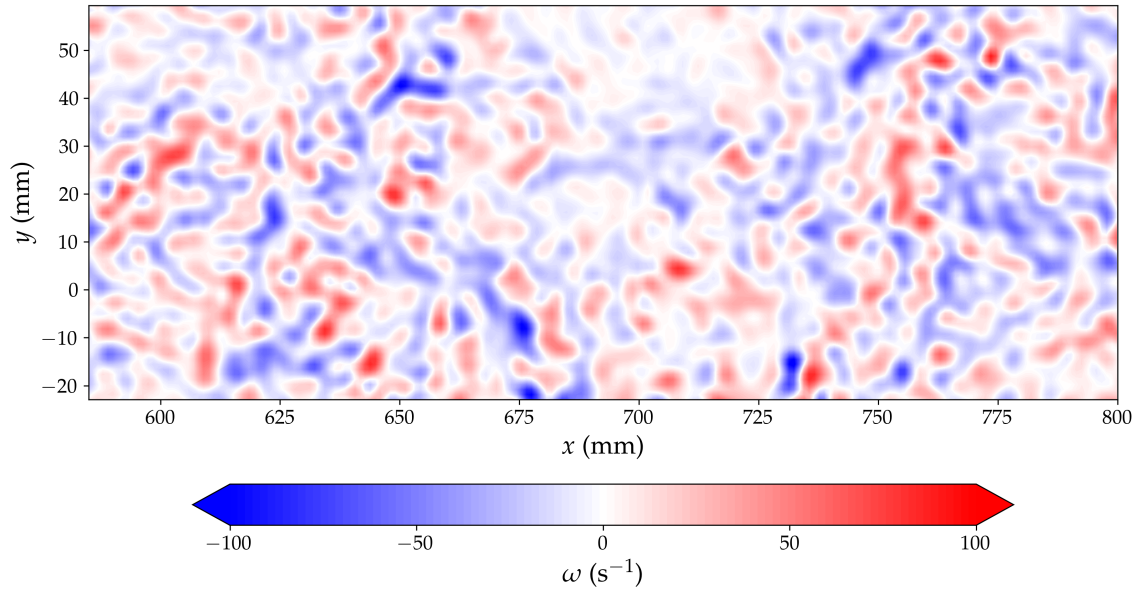


Figure 6. Snapshot of the out-of-plane vorticity downstream the jet array for jet Reynolds numbers of 6.65×10^4 .

5. Summary

This paper summarizes the work in progress of designing an experimental test rig to investigate droplet fragmentation in homogeneous isotropic turbulence. The overall design follows the suggestions of other researchers who previously built experiments producing HIT. However, none of the documented test rigs based on two opposing randomly actuated synthetic jet arrays was used for investigating the cascade of droplet breakup in the past. Therefore, we need to consider additional aspects to ensure the applicability of the RASJA design for the turbulent emulsification problem. Based on the calculated Kolmogorov-Hinze scale we can estimate a minimal droplet size that needs to be injected. Besides providing high dissipation rates, we propose to also consider the residence time of droplets in the turbulent region with respect to the turbulence decay time scale proportional to TKE and ε . Preliminary flow field measurements of a single jet allow to estimate the relevant quantities. The HIT tank is currently in commission with one pump array in operation and the second one currently being assembled. Preliminary measurements using 2D PIV show promising results in the expected range, with some remaining mean flow that we expect to disappear when using both jet arrays in the final setup. Future experiments will focus on further characterization of the HIT region by measuring turbulence statistics and spectral analysis of vorticity and enstrophy dynamics in both single-phase and droplet-laden flows. The latter will be enabled by combining tomographic PIV with three-dimensional droplet shape reconstruction.

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