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Luis Blay Esteban

Dynamics of Non-Spherical Particles in Turbulence

Doctoral Thesis accepted by
University of Southampton, UK

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To Mum and Dad…

Supervisor's Foreword

One of the beautiful things about fluid mechanics is the discovery of complexity in the most simple things. In this thesis, we investigate the motion of falling planar objects in still and turbulent fluid—much like a coin being dropped into water and this descending down describing a "fluttering" type of motion. The project was inspired by a supporting company, who reprocess mixed waste that contains metal, plastics, glass, and organics to separate out these streams and then sell the metal and washed glass. They use a turbulent water tank and make use of the different ways in which metal, glass, and plastic particles move in this flow to separate them. This thesis provides interesting findings that help to understand how particle shape and background turbulence affect the particle descent style.

The Ph.D. research was entirely experimental and makes use of the power of modern-day digital cameras. These were used to record the descending particle and bespoke software to track the particle position, velocity, and acceleration along the 3D trajectory. In still fluid, we found that the motion of disks follows a pendulum motion where the origin of the "string" connecting the particle is falling with the mean fall velocity of the particle. Further studies investigated the effect of other planar shapes, such as squares and hexagons and compared these to the classical disk shape. It was found that the particle shape has an impact on the key characteristics of the particle trajectory. Also, 3D flow field measurements behind the particle revealed the influence of the frontal shape on the wake structure shed.

The work on particle descent in turbulent flows required a large volume of controlled isotropic turbulence in which to study the motion of the particle. A large tank agitated by a dual array of bilge pumps was constructed and this permitted the study of the decaying isotropic turbulence for a far longer time that is possible in typical wind tunnel configurations. The turbulence generated was characterized in detail, and the evolution of the decaying turbulence was carefully investigated.

Finally, the study of particle motion in turbulent flows revealed that the falling style becomes a combination of "noisy" pendulum motions and "rare" events; these being sections at high velocity or "levitating" states, before being "caught" and resuming the "noisy" pendulum motion.

Southampton, UK Prof. John Shrimpton
June 2019

Parts of this thesis have been published in the following journal articles:

1. **L.B. Esteban**, J. S. Shrimpton, P. Rogers and R. Ingram. Three Clean Products From Co-mingled Waste Using A Novel Hydrodynamic Separator. International Journal of Sustainable Development and Planning. Vol 11: 792–803 (2016)
2. **L.B. Esteban**, J. S. Shrimpton, B. Ganapathisubramani. Edge effects on the fluttering characteristics of freely falling planar particles. Physical Review Fluids 3, 064302 (2018)
3. **L.B. Esteban**, J. S. Shrimpton, B. Ganapathisubramani. Study of the circularity effect on drag of disk-like particles. International Journal of Multiphase Flow, 110: 189–197 (2019)
4. **L.B. Esteban**, J. S. Shrimpton, B. Ganapathisubramani. Laboratory experiments on the temporal decay of homogeneous anisotropic turbulence. Journal of Fluid Mechanics, 862: 99–127 (2019)
5. **L.B. Esteban**, J. S. Shrimpton, B. Ganapathisubramani. Three dimensional wakes of freely falling planar polygons. Experiments in Fluids, 60: 114 (2019)

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I met Prof. John Shrimpton once this project was done and after a few meetings he accepted my application to undertake my Ph.D. studies under his (and Bharath's) supervision. I only have nice words to explain how they treated me during these 3 years. They gave me very good guidance but always with the necessary freedom that allows you to fail, learn, and improve. They supported my ideas and they were always there when I needed them. Thanks for all these moments, from the long discussions in the faculty to the always welcomed visits to the lab.

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Contents

Abbreviations

BBO	Basset, Boussinesq, and Oseen equation
CDF	Cumulative Density Function
CSF	Corey Shape Function
DNS	Direct Numerical Simulation
FOV	Field of View
HD	Homogeneity Deviation
HIT	Homogeneous Isotropic Turbulence
LES	Large Eddy Simulations
MFF	Mean Flow Factor
M-R	Maxey-Riley equation
MRF	Material Recovery Facility
MSRF	Mean Strain Rate Factor
OU	Ornstein Uhlenbeck process
PDF	Probability Density Function
PIV	Particle Image Velocimetry
PLA	Polylactide
SFT	Structure Function Fit
TKE	Turbulent Kinetic Energy

Non-dimensional Quantities

Ar	Archimedes number
C_D	Drag Coefficient
Fr	Froude number
G	Galileo number
Q	Isoperimetric quotient
Re	Reynolds number
St	Stokes number
St	Strouhal number
X	Best number

Roman Symbols

b	Particle body force
d	Particle diameter
d_{eq}	General particle equivalent diameter
$d_{V_{eq}}$	Sphere diameter with equivalent volume
f	Frequency
g	Acceleration due to gravity
k	Turbulent kinetic energy
ℓ	Particle equivalent diameter (D_c/Q)
m	Mass
t	Particle thickness
t_L	Eddy turnover time
A_p	Projected area
D	Disk diameter with equivalent particle volume
D_c	Diameter of circumscribed disk
E	Energy spectrum
F_D	Drag force
I	Mass moment of inertia
L	Integral length scale
P	Particle perimeter
Q_{dis}	Water discharge
R	Distance from origin
S	Skewness factor
T	Energy transfer spectrum
T_i	Torque
T_{v_z}	Timescale of descent velocity fluctuations
U	Velocity
U_t	Terminal velocity

Greek Symbols

α_{v_z}	Std. of descent velocity fluctuations
β	Thickness-to-width ratio
ϵ	Energy dissipation rate
η	Kolmogorov length scale
θ	Particle nutation angle
θ_0	Max. angle of pendulum model
κ	Kurtosis
λ	Taylor length scale
μ	Viscosity
v	Kinematic viscosity
ρ	Density
σ	Total stress tensor
τ	Response time
τ_d	Fluid timescale at scale d
$\tau_{p_{eff}}$	Measured particle response time
τ_f	Fluid response time
τ_v	Viscous relaxation time
τ_w	Wall shear stress
ϕ	Fractional number of pumps in operation
ϕ_v	Fractional volume of the dispersed phase
ψ	Sphericity
ω	Angular velocity
Λ	Production rate of total kinetic energy

Subscripts

d	Based on particle diameter scale
f	Fluid magnitude
min	Smallest value
med	Intermediate value
max	Maximum value
p	Particle magnitude
q	Magnitude in quiescent flow
r	Relative to disk magnitude
z	Vertical magnitude
L	Based on integral scale
η	Based on Kolmogorov scale
λ	Based on Taylor scale
$\|$	Parallel to the motion
$\perp$	Perpendicular to the motion
1	Along the horizontal direction
2	Along the vertical direction

Superscripts

$\cdot^*$ Non-dimensional value
$\cdot'$ Root mean square

Operators

∇	Divergence
$\langle \cdot \rangle$	Spatial average
$\bar{\cdot}$	Time average
$\mathbf{v}$	Vector form of v