Study of the mechanics of the enigmatic vortex phenomena from terrestrial/astronomical scales to microscopic scales, including fluid mechanics in sports

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Summary of Research

Study of Vortexes Across a Wide Range of Fields

Numerous phenomena in various domains incorporate fluid vortexes, ranging from the terrestrial/astronomical scale to the micro scale.

Our laboratory undertakes theoretical and numerical simulation studies as well as experiments to better understand the materials and energy transport phenomena present in all fluid motions. Our study of vortexes has also expanded into a unique area: fluid mechanics in sports.

Terrestrial-Scale Vortexes

One of the major themes of research at our laboratory is the analysis of vortexes in the atmosphere and in oceans, patterns that bear directly on global environmental issues. In vortexes at the terrestrial scale, vertical motion is inhibited by rotation and stable stratification (lower temperature in lower layers and higher temperature in higher layers), stabilizing the vortex structure and resulting in longer vortex lifespans. To give an example, a vortex formed within the atmosphere generally lasts about one week, while a medium-scale vortex (measuring approx. 100 km in diameter) generated in the ocean can persist for 2–3 years. Our laboratory pursues statistical studies of the mechanisms responsible for the formation and prolonged life of these vortex structures.

One of our theoretical studies focuses on systems in which multiple vortexes co-exist, assuming that the most stable state of the system is the one having the highest entropy. It is our hope that these studies will contribute to a more accurate prediction of global climate change.

Micro-Scale Vortexes

For micro-scale fluid motions, we are studying the mixing phenomenon that occurs in a droplet (a drop of liquid measuring about 2 mm in diameter) as the result of internal flows induced by the oscillations resulting from surface tension, from both experimental and theoretical perspectives. To produce the mixing phenomenon generated inside a droplet by surface tension waves, multiple oscillation modes must exist:

The particles in the liquid must be made to follow paths in the Lagrangian chaos state, so that material transfers occur chaotically. Developing a method to achieve this goal would allow non-contact mixing inside small particulate droplets and open up vast potential in the area of applications—for example, in pharmaceutical manufacturing processes.

At even smaller scales, we are studying fluid phenomena on the order of micrometers (μm). For gaseous fluids in the micrometer world, flow must be regarded as the motion of a group of molecules. At such scales, we begin to see phenomena not encountered in the macroscopic world: The behavior of gas in the microscopic world resembles that of low-pressure gas.

In the micro-scale world, the mean free path of molecules (the distance a molecule travels before striking another molecule) is large, generating phenomena similar to those observed in low-pressure gases, in which the sparse distribution of the molecules also results in large mean free path. Focusing on these common features of microscopic fluid motion and low-pressure gas, we are pursuing studies on both systems based on experiments and numerical simulations.

Fluid Mechanics in Sports

When studying a breaking ball thrown by a baseball pitcher, most people tend to focus on rotation. However, the behavior of the air surrounding the ball, or the fluid motion generated by the ball, is essential to a full understanding of the physics of

Keywords

Vortex motion; environmental fluid mechanics; terrestrial scale; turbulence; fluid mechanics in sports; fluid mechanics; vortex; droplet; mixing; numerical simulation; chaos; Lagrangian chaos; PSP (pressure-sensitive paint); Knudsen pump; radiometer; low-pressure gas; Coulomb interaction; environmental issues

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a breaking ball. The direction and rotation of the seams on a baseball affect airflow around the ball (generating turbulent or laminar flow), and resulting in the ball's erratic trajectory.

Our laboratory is seeking to elucidate the mechanism underlying the movement of breaking balls by investigating the relationship between vortexes and the fluid phenomena that occur around the ball. We are also expanding our research focus to include vortexes encountered in other sports that involve objects in flight, such as table tennis and archery.

Advantages

Joint Research Projects and Extensive Connections to Individuals in Various Disciplines Established Through Our Research in Fluid Mechanics

The vast range of scales encompassed by the phenomena targeted by our research reflects one of the key characteristics of our laboratory. As briefly discussed above, we pursue research on vortexes from scales ranging from the astronomical to the terrestrial to the microscopic, studies with a broad range of applications.

This has led to numerous joint research projects and established extensive connections to individuals draw from various disciplines. We maintain close ties with the National Institute for Environmental Studies, the Atmosphere and Ocean Research Institute of the University of Tokyo, RIKEN, and members of the Japan Society of Fluid Mechanics.

We have engaged in joint research with JAXA (the Japan Aerospace Exploration Agency) and the Institute of Fluid Science of Tohoku University, which have kindly granted us access to their research facilities. These joint studies have produced results such as those presented in the paper, "Aerodynamic Properties of an Arrow: Influence of Point-shape on Boundary Layer Transitions (Nagare, vol. 29, pp. 287-296; 2010)

Wind Tunnel and Videography for Measurements in Fluid Mechanics Experiments Involving Sports

Another interesting current study undertaken jointly with the Japan Institute of Sports Sciences investigates arrows. In this study, experiments determine the force of air (resistance, lift, moment) experienced by an arrow during flight, while measurements are taken inside a wind tunnel.

Generally, the precision of such experiments involving wind tunnels is limited by the resistance presented by the supporting apparatus of the arrow. We can overcome this problem by using JAXA's GRAPE-DR, a computer capable of efficiently performing complex molecular dynamic simulations. Since the interactions present in a vortex are quite similar to Coulomb interactions, the GRAPE-DR can also handle the calculations required to simulate a complex vortex.

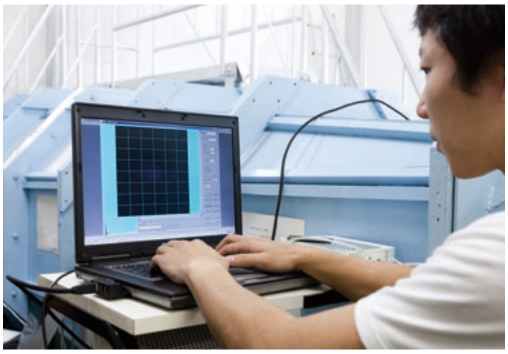
Future Prospects

Developing a Totally New Pressure Measurement Method

A major goal for the near future is to complete the development of a novel pressure measurement technique using PSP (pressure-sensitive paint), a joint project involving JAXA. With this PSP method, to measure the pressure applied to a surface, we simply apply a coat of paint to the surface of that object.

To measure pressure, the PSP is irradiated with excitation light, after which we measure the light emitted from the chemicals. The amount of emitted light depends on the concentration of oxygen around the PSP. To take an instant pressure distribution measurement at a surface by this method, we simply apply paint and irradiate the surface with light.

This technique, if made feasible, will allow researchers to measure pressure under conditions in which pressure measurements were previously impossible. Work to develop this pressure assessment method is among the priority themes of research and development at our laboratory.



A scene from a wind tunnel experiment involving a magnetic suspension and balance system at JAXA

Internal view of wind tunnel experiment involving a magnetic suspension and balance system

Actual arrow-firing experiment at the Japan Institute of Sports Sciences