Experiments in fluid mechanics

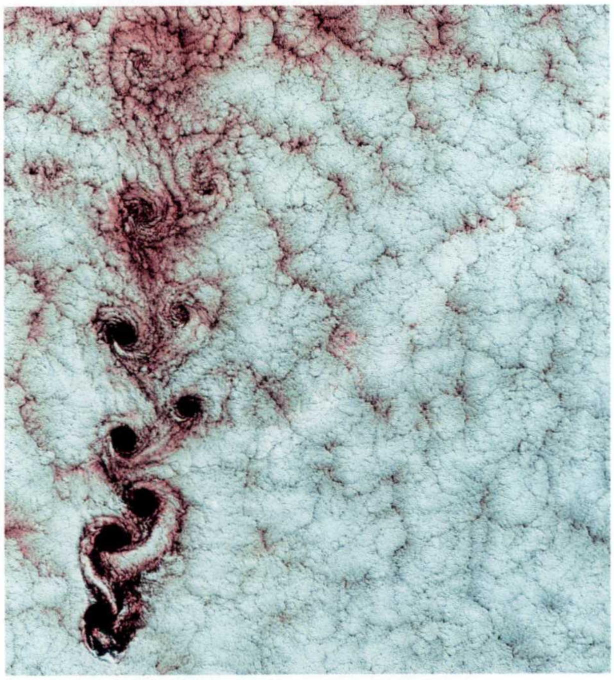
Fluids in Motion

TOMASZ A. KOWALEWSKI
Institute of Fundamental Technological Research, Warszawa
Polish Academy of Sciences
tkowale@ippt.gov.pl

Fluid motions are responsible for most of the transport and mixing that take place in the environment, in industrial processes and vehicles, and within living organisms

They are present almost everywhere, being responsible for our climate, oceans and rivers, for the development of aircraft, ships and automobiles, and for the transportation of water, oil and oxygen.

Fluid motion is also an important element of any heating or cooling system. The discipline devoted to describing these exciting phenomena is called fluid mechanics.



USGS EROS Data Center Satellite Systems Branch

These swirling clouds appeared over Alexander Selkirk Island in the southern Pacific Ocean. The island's highest point is 1.6 km above sea level. As wind-driven clouds encounter this obstacle, they flow around it to form large, spinning eddies. This is a false-color composite image made using short-wave infrared, infrared, and near-infrared wavelengths. Modelling of such vortices requires numerical methods of the fluid mechanics

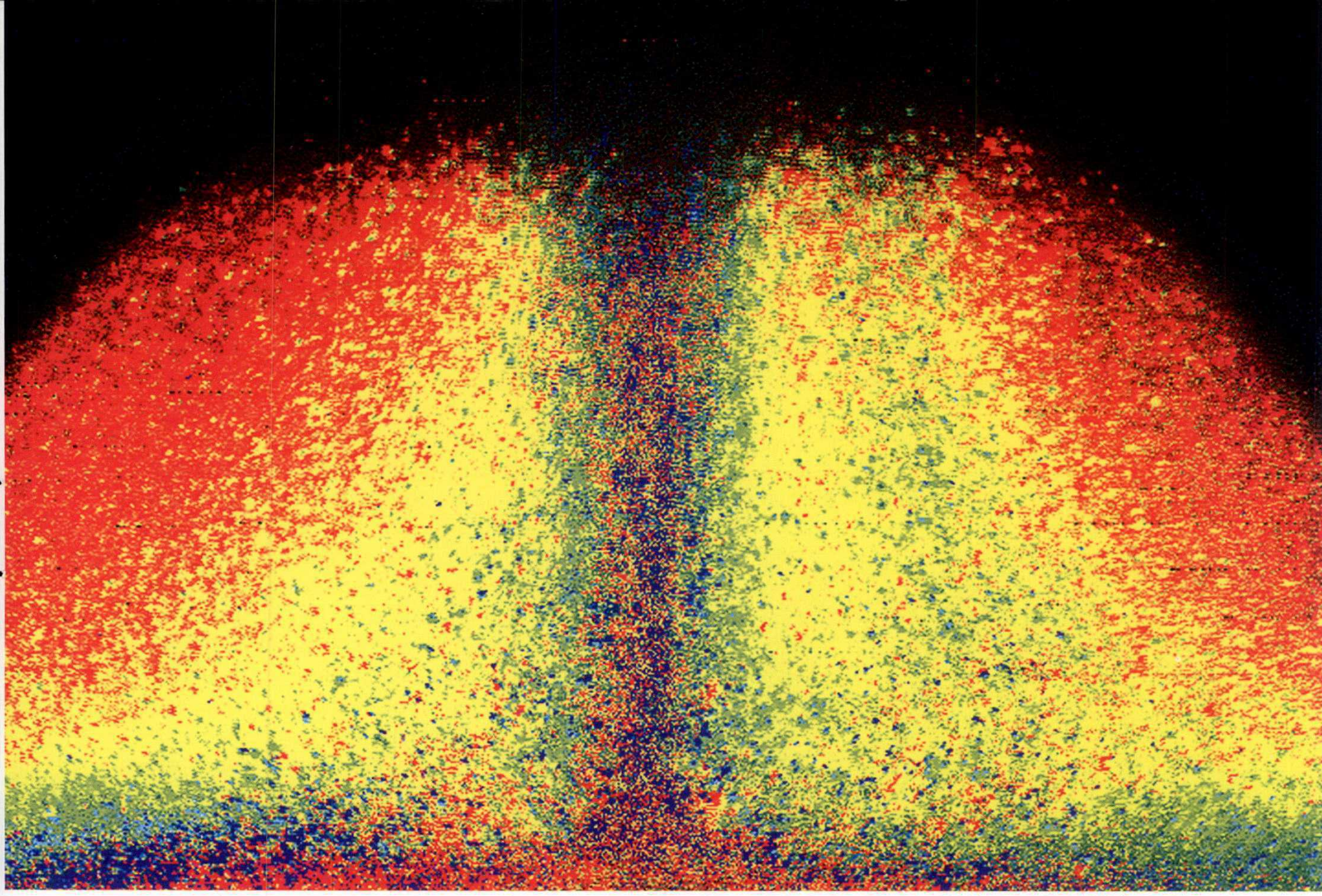
This is a comparatively old discipline, whose roots go back to ancient achievements with hydraulic systems. Originally, it was based on "craftsman's" intuition and "trail and error" experimentation. Presently, modern fluid mechanics strives to use knowledge of physical principles to describe and predict any phenomena involving fluid motion. However, despite the revolutionary development of science seen in the last century, our ability to predict many flows is still very limited. This is mainly due to the mathematical difficulties involved in finding a full solution to the basic governing equation. Remarkably, a one million dollar prize established decades ago to encourage mathematicians to find a proof that a solution does indeed exist still remains unclaimed! It is therefore not surprising that with the arrival of powerful computers, computational fluid dynamics (CFD) has become an attractive alternative for furthering research in theoretical and experimental fluid mechanics, by offering approximate methods for solving "unsolvable" problems.

Any numerical solution is always only an approximation of the analyzed phenomena, due to the inevitable simplifications of the physical problem

Presently, any flow problem can, in principle, be solved numerically. Turbulence also appears to be revealing its secrets to numerical experiments, provided that all relevant scales are fully resolved. A huge number of commercially available codes purport to solve almost every problem imaginable, suggesting that the epoch of expensive and complicated laboratory experimentation has passed. But do we trust simplified numerical simulations in fluid dynamics?

The sources of the discrepancies between observed and numerical flow structures are plentiful. Fluid motions tend to be very sensitive and responsive, sometimes to even minute alterations of flow rate, boundary shapes, or boundary temperatures - to virtually all conditions of the motion. This sensitivity is due to the tendency of fluid motion states to be unstable.

Such instability implies difficult-to-predict deviations of the predicted flow from its physical realization. Of course, in many cases coarse numerical results, resulting from simplified and idealized models, are accepted and successfully applied in engineering applications. However, a broad class of problems exists where knowledge of



Visualization of a thermal jet generated by local heating of the bottom surface. The hot liquid accelerates creating a "micro tornado" above the surface. The experiment clearly indicates regions of high temperature and velocity (blue color). Such vertical temperature differences are mainly responsible for atmospheric or oceanographic fluid motion

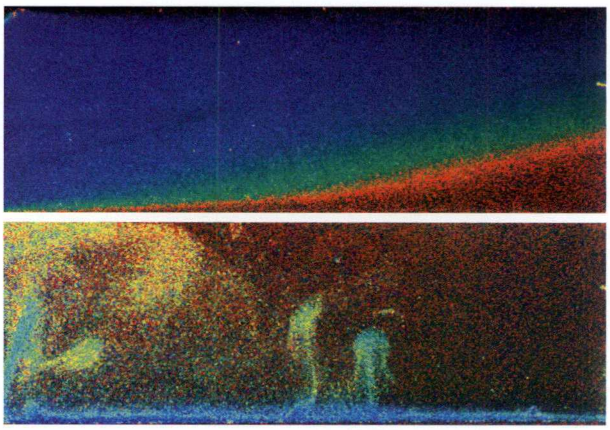
general flow behavior alone is not sufficient to obtain a full quantitative elucidation and effective control of the phenomena. Thus, for example, the quality of produced sheets of metal or silicon crystals is largely dependent on the fine-tuning of fluid motion. Instabilities at the solid/liquid interface can lead to micro-segregation patterns in the deposition of impurities, which may later be detrimental to the material produced. The growing demand for high-quality alloys and semiconductors encourages us to seek ways of predicting and controlling their production.

How can reliable flow prediction be achieved?

It is impractical and usually impossible to include all possible factors when modeling complex flow phenomena by computational means. Also it is impossible to analyze all the flow details of complex industrial or environmental fluid motion to verify a computational model. It appears that simple, well described experiments which deliver full details of the flow structure can be used for validating computational models. A properly planned reference experiment, called an *experimental benchmark*, alerts us to the flow's sensitivity to the implemented simplifications, which would otherwise be hard to predict.

To define an experimental benchmark, details about the complex flow must be measured. Velocity and temperature are the primary fields which characterize a thermally driven flow. The collection of experimental data is an important issue. Point measurements were the traditional method of investigating fluid motion in the past. Despite their high accuracy, the limited number of simultaneously acquired values made their use questionable for the purposes of validation. Therefore, full field acquisition methods are now in favor, especially in the case of phenomena changing in time.

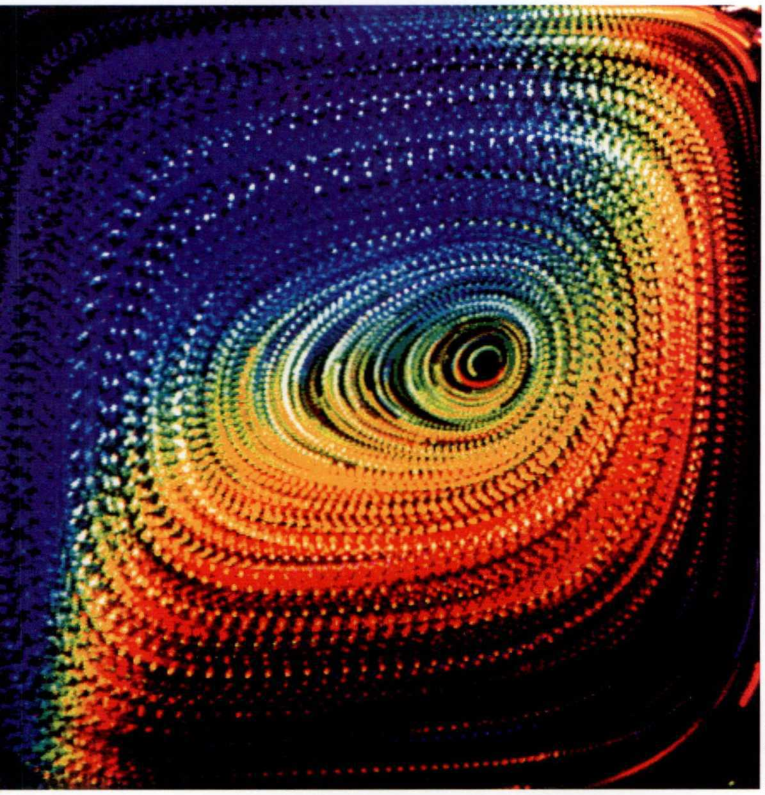
The use of such data for model validation becomes questionable. The same principle applies to any complex flow configuration. Only complete information from the whole fluid-filled volume can offer an unambiguous



Laboratory model showing temperature distribution above a slope: (upper photo) a cold bottom (tracers of red color) and warm fluid above – a typical stable, nocturnal configuration of the atmosphere; (below) up-draughts typical for the morning transition

experimental reference for comparison with computed predictions. This is something easy to say, of course - but actually collecting dense experimental data about a flow without disturbing the fluid motion itself proves to be a difficult task.

One of the modern experimental tools that yield a full field quantitative measurement of velocity fields is known as Particle Image Velocimetry (PIV). This method



TK experiment

Fluid motion observed in the center plane of a cubic cavity. The left vertical wall of the cube is kept at a higher temperature, and the right vertical wall at a lower temperature. The fluid density difference generates fluid circulation from the hot wall to the cold one, and back.
Such a configuration is typical for air circulation in a room, where a heater (or cooler) is located at one of the walls. Liquid crystal tracers, visible in the figure as small dots, change their color from dark blue in the high temperature region to yellow and red as the fluid cools down.
The computational analysis of such images allows us to identify the fluid velocity and temperature at any point of the flow

is based on the computational analysis of tracer motion. In our laboratory the method has been extended to include simultaneous full field measurements of fluid temperature. Here, the tracers used are suspended liquid crystals which change their color with the local fluid temperature. Complete two-dimensional temperature and velocity fields are determined from two successive color images taken at a selected cross-section through the analyzed flow. These velocity and temperature distributions are easy to compare with their numerical counterparts, permitting a profound analysis of computational models' reliability. The examples shown here illustrate the application of the method to a few typical flow configurations. In all these examples fluid motion arises because the flowing material is lighter (tending to rise) or heavier (tending to sink) from place to place, because the fluid temperature is not uniform.

More complex flow structures are formed on slopes of valleys, where solar radiation generates strong up-slope flow during the day, while nocturnal cooling of the ground induces the reverse flow. Small-scale experiments performed in an inclined cavity illustrate the main futures of diurnal flow changes. A quasi-periodic sequence of rising hot plumes is observed in the experiment, simulating a transition from stable to unstable thermal stratification, typical for the morning transition of a valley slope. Both velocity and temperature fields indicate the presence of thermal up-draughts and downdraughts. This type of instability depends on the slope inclination and thermal parameters and is the primary agent responsible for the vertical mixing processes in the atmosphere's ground layer - the region most important for our perception of local weather conditions. The experiment is used to analyze the performance of numerical models in simulating atmospheric flows in complex terrains.

It is easy to imagine the motion of the atmosphere looking at full field data obtained from satellite images. Understanding the same motion using only point measurements obtained for a sparse grid of meteorological towers presents a real challenge

The experimental technique developed in our laboratory, based on image processed data, yields quantitative, full-field information about the temperature and velocity fields. The non-invasive character of the method and its relative simplicity offers a valuable tool for the full field verification and validation of numerical results for small-scale laboratory configurations. We have found that large improvements in the quality and reliability of numerical simulation could be obtained by means of validation and tuning methodologies, using information obtained from such experiments. ■

Further reading:

Kowalewski, T.A. (1998). Experimental validation of numerical codes in thermally driven flows. *Advances in Computational Heat Transfer. 1-15.* New York: Begel House Inc.

Kowalewski, T.A. (2002). Particle Image Velocimetry and Thermometry in Two Phase Problems. *Visualization and Imaging in Transport Phenomena, Annals of New York Academy of Sciences, 972,* 213-222.