ROUGHING IT

By Lori Oliwenstein

Beverley McKeon has made a career of creating turbulence—and that's a good thing, at least when it comes to golf balls and insect-sized aircraft.

Television and print journalists listen intently as Beverley McKeon explains the aerodynamics of an older, conventional soccer ball.

It was June 23, 2010. World Cup fever was, appropriately, at a fever pitch. So was the controversy over the reportedly odd behavior of the event's brand-new Jabulani ball—manufactured by Adidas, reviled by almost every goalie to touch it (or not), and half-jokingly rumored to have played a role in the recent, unexpected tie game between the U.S. and England, during which a relatively routine shot on goal got past England's keeper.

Deep within Caltech's Guggenheim Aeronautical Laboratory, at least a dozen cameramen, photographers, and reporters—and a dozen more onlookers—were crammed into the cramped spaces surrounding the Lucas Wind Tunnel, or peering down from wooden viewing platforms overhead.

They were all intently watching one woman: assistant professor of aeronautics—and fervent soccer fan—Beverley McKeon.

She, in turn, was focused on the tunnel's viewport, wherein smoke could be seen swirling over, under, and around a Jabulani that had been mounted on a support rod. After a short while and a few technical glitches—and after having already seen how the smoke flowed around an iconic black-and-white ball—she was ready to talk about her observations.

A soccer ball, McKeon explained to the gathered onlookers, is in no way a perfect sphere. It is a collection of stitched-together panels: 32 for the backyard-scrimmage ball used by most of us, but only eight for the Jabulani. Furthermore, the grooves between the Jabulani's panels are not nearly as deep as the ones on its predecessors.

Put all of that together, McKeon continued, and you get a ball that can behave unexpectedly—its interactions with the air through which it hurtles increase the drag and alter the lateral forces that act on the ball, slowing it down and curving its flight path in an unexpected way.

"So as the goalkeeper sees the ball coming, it suddenly seems to change its trajectory," McKeon told the reporters as they studied the Jabulani's shallow-grooved profile. "It's like putting the brakes on, but putting them on unevenly." And that, she added, was as good an explanation as any for England's near-loss.

"I'm sure it's entirely down to the ball and had nothing to do with our goalkeeper," the British-born scientist concluded, with only a hint of a grin.

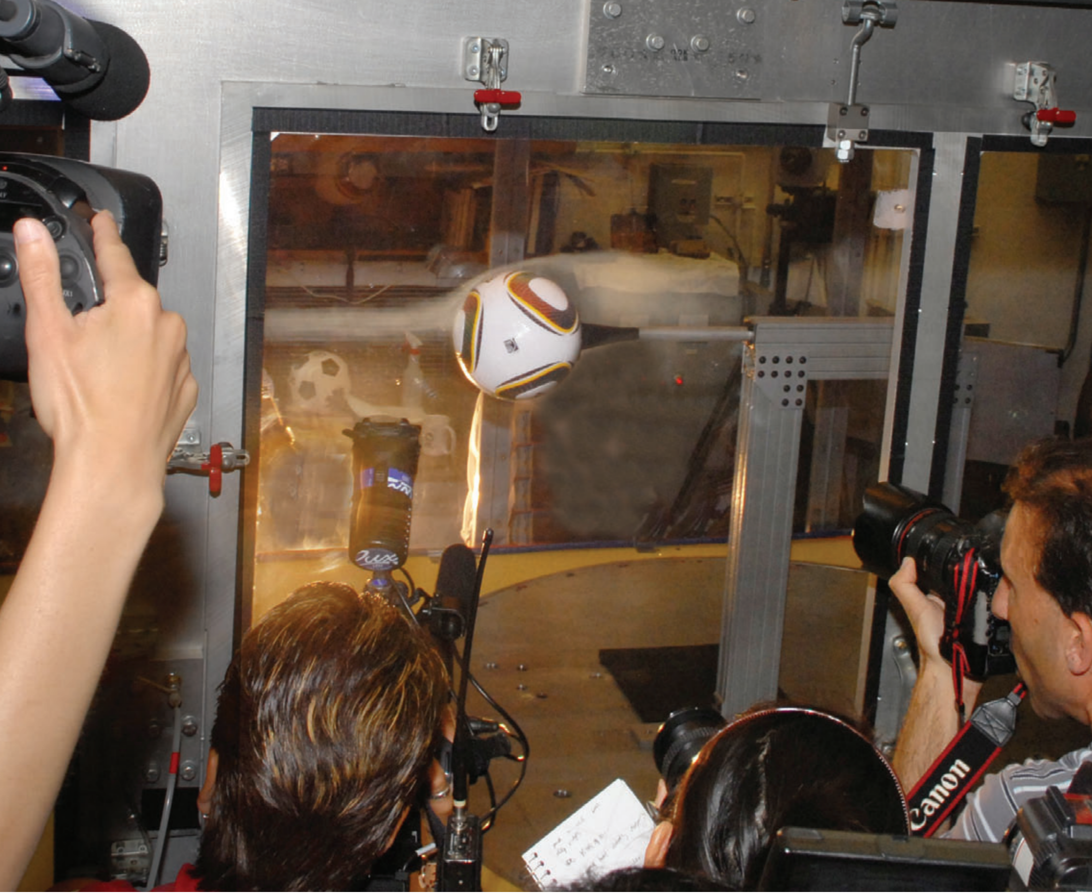
EMBRACING TURBULENCE

National pride aside, McKeon was a natural choice for the spotlight during this classically Caltech amalgamation of science and soccer. Besides being a self-proclaimed "huge sports fan," she studies wall-bounded flow: the way air behaves as it glides over—or, at times, twirls above, swirls around, or snags on—the surface of an object, its molecules either forming into layers or mixing things up as they go.

Of course, as she quickly pointed out, the Jabulani test was far from conclusive, and it would have been so even if the smoke machine hadn't benched itself early in the experiment. On a soccer field, a ball spins and changes speed as it flies, and it has to deal with changing winds, humidity, and the occasional errant insect. McKeon's test, on the other hand, involved a stock-still ball in a steady, 30-meter-per-second wind—a speed based on the average velocity of a ball kicked by a professional soccer player.

Still, even in McKeon's idealized scenario, the Jabulani followed the rules of fluid mechanics, which say that there are two main ways in which air can flow over pretty much any surface, including a soccer ball. The air can move in two dimensions, its particles sliding effortlessly over one another and the ball in smooth, parallel layers; this is called laminar flow. Or it can move more erratically, its individual particles tumbling about in three dimensions and resembling nothing so much as roaches skittering across the kitchen floor when a light goes on. This is turbulent flow.

We tend to think of turbulence as something to be avoided at all costs. And, in a pipeline transporting water or oil from one place to another, that is the case. When things get turbulent inside a pipe, the energy needed to pump the pipe's contents from point A to point B kicks up dramatically. Not good. But when it comes to soccer balls and their ilk, turbulence can have its benefits.



When a laminar flow in the boundary layer—the area closest to the ball's surface—hits the ball's equator, the smooth-gliding layers of air immediately peel apart from one another and away from the skin of the ball; the air molecules just keep traveling straight ahead, creating a wake that is, essentially, the width of the ball itself. And, in turn, that wake drags on the ball, slowing it down.

A turbulent flow in that same boundary layer, on the other hand, hugs the ball's surface for as long as it can, its air particles energized by all their jitterbugging. "A turbulent flow travels a little farther into the pressure gradient that pushes the laminar flow away from the ball, so it separates from the surface *past* the ball's equator," McKeon explains. "This creates a smaller, narrower wake. And because the wake is smaller, the drag on the sphere is lessened, as well."

Laminar flows tend to be slower, and they do best when traveling over smooth surfaces, whereas turbulence comes from rougher surfaces and higher flow speeds. Things get interesting—and confusing—in the middle ground, where the flow can go either way, and where just the slightest push can more quickly and easily turn a laminar flow turbulent.

McKeon and her colleagues have staked their claim to that middle ground. Their research into the effects of roughness on turbulent flow—done at GALCIT, the Graduate Aerospace Laboratories of the California Institute of Technology—is performed in tunnels of wind and water, into which they inject smoke or dye to see what the fluids they're studying are up to. And yes, to McKeon, air is a fluid, albeit a very runny one. "When we say fluid, we mean any liquid or gas," she notes. The mathematics shaping the flow are exactly the same whether you are watching wind or water pass over the surface. Which medium you use, says McKeon, depends chiefly on your experimental needs: Swirls and eddies can best be seen in flowing water with a shot of dye. But if you want to examine a high-speed flow, water may be too sluggish; in that case, air and smoke may be your best bet.

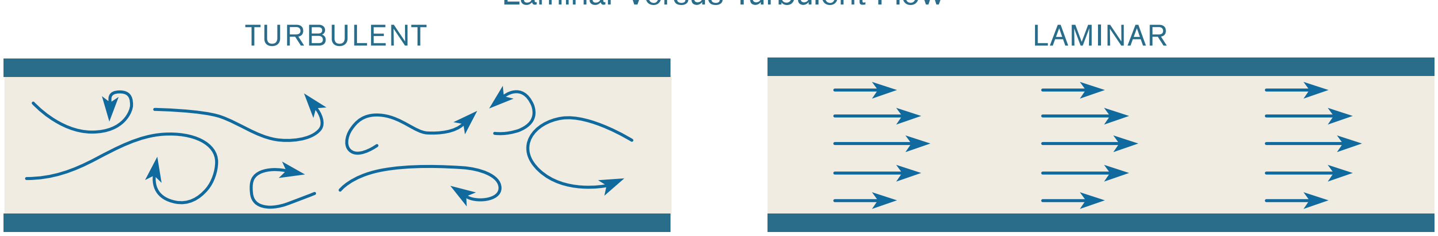
Swirl by complex swirl, layer by minuscule layer, McKeon is trying to understand just why the smooth, parallel lines of a laminar flow take on the helter-skelter unpredictability of a turbulent flow—and how we can make those flows behave the way we want them to, when we want them to. For her efforts, which range from building a better golf ball to reducing drag on a Boeing 747, McKeon was given the Presidential Early Career Award for Scientists and Engineers in 2009.

A DIMPLE DILEMMA

You might think that fussing around with the likes of golf balls and soccer balls is more child's play than serious science. You'd be wrong. These things are, certainly, "great teaching tools," says McKeon. But they are anything but simple.

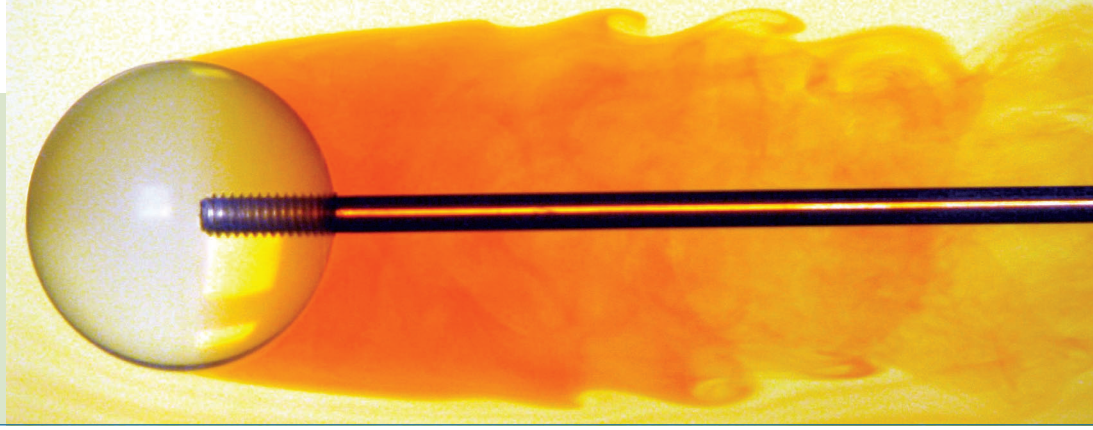
"The irony is, although spheres are used in sports all over the place, they present a very difficult problem from a fluid-dynamics perspective," she says.

Laminar Versus Turbulent Flow



Left: The Jabulani soccer ball is ready for its close-up in the Lucas Wind Tunnel.

Right: Dye-laden water, flowing past what is known as a "bluff body," allows scientists to really see the way the fluid interacts with the surface of the sphere.



"You have a tiny layer of fluid very close to the ball with a big wake behind it governing the forces that are generated; it's hard to investigate the flow experimentally or numerically, and it's very sensitive to surface conditions."

A golf ball, for instance, exploits a complex combination of aerodynamic forces to make its way from tee to green. But it wasn't always that way. In fact, the golf ball began its illustrious career as more of a runtish, rigid racquetball, picking up its distinctive dimples only after players began noticing that balls nicked during use, or pockmarked with clumps of mud and grass, flew farther and straighter than clean balls.

"The Scots learned about fluid dynamics the hard way," McKeon quips.

It turns out that the mud (or the dimples) bump the boundary layer—the zone of air hugging the ball's surface—from laminar to turbulent flow as early in the ball's flight as possible. This leads to a wake that is as thin as possible, which in turn leads to a dramatic reduction in drag.

How dramatic? "If you hit a golf ball without dimples, it will go less than half the distance of a ball with dimples," says McKeon.

As impressive as that is, McKeon and her team—including graduate students Ian Jacobi (MS '08), Jean-Loup Bourguignon (MS '08), Jeff LeHew (MS '07), and Rebecca Rought (MS '09), who work on turbulent flow and surface design—are trying to do the Scots one better. Their goal: a dynamic golf ball, one whose dimples change depth asymmetrically in response to changing conditions during flight.

This mighty morphin' golf ball would start on the tee looking much like a regular ball, with uniformly distributed dimples, McKeon explains. But, once hit, "if the ball were to begin to veer off target, you might trigger one side to be more rough than another. That would lead to more turbulence on that side, creating a lateral force that would steer the ball back on track."

Her team has found that it doesn't take much to give the ball a sideways push. "We can get a very large lateral control of the ball's trajectory with only a very small asymmetrical change to the ball itself," McKeon notes.

And when McKeon says small, she means *small*. In a recent study published in the *Journal of Fluid Mechanics*, a McKeon lab team that included graduate student Adam Norman (MS '06, PhD '10) added a single bump to an otherwise smooth sphere—a bump that took up all of two thousandths of a percent of the sphere's surface area and had a diameter and height equal to just one percent of the sphere's diameter.

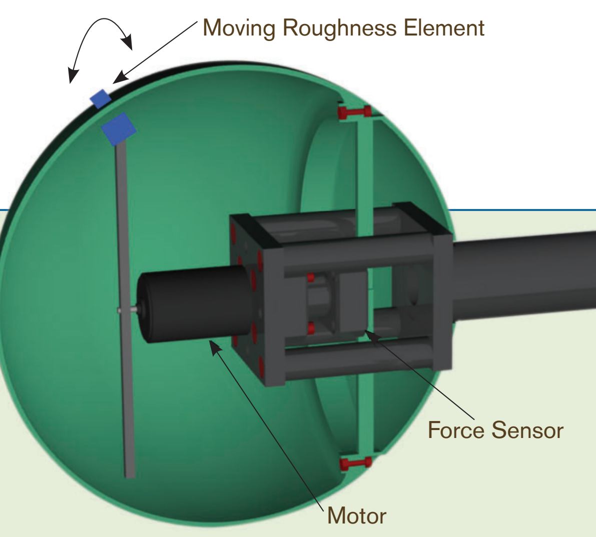
But that bump—a metal stud held in place by a magnet inside the sphere—had a huge impact. The team used the magnet to drag the stud around the sphere, just upstream of the equator. The projecting stud created localized regions of turbulence in the boundary layer around the sphere. As the stud moved, the turbulence moved with it, altering the lateral forces and drag the sphere experienced. "Adam's work showed that it was possible to use a true morphing surface to control the forces acting on an object," says McKeon.

But don't head to your local sporting goods store quite yet, Tiger. It's one thing to mess with the dimples on a golf ball. It's another thing entirely to create a ball whose surface literally shape-shifts over time, and does so asymmetrically. A ball like that needs to be responsive to the conditions around it. A ball like that needs more than the brute-force mechanical maneuverings of magnets and studs. A ball like that needs to be smart.

Enter Caltech materials scientists Kaushik Bhattacharya and Michael Ortiz. McKeon challenged them to create "smart" materials that can rapidly change the flow around themselves in response to changing environments or changing needs—not just on a golf ball, but as part of any number of potential applications.

In yet-to-be-published research, the members of this multidisciplinary team have shown they can do just that. With the help of visiting student Andre Bauknecht from the University of Stuttgart, Germany, they've created inch-sized swatches of material that can respond to a stimulus—such as heating, stretching or contracting, or perhaps the application of an electrical field—by changing its surface roughness. "We've shown that when this morphing material is activated, the lift and drag on the object change," says McKeon.

But taking this breakthrough and turning it into a golf ball that knows when and where to change its surface roughness is a long way off, and no easy task.



To examine the effect of a small, dynamic change in a sphere's roughness, McKeon's group attaches a metal stud—the "moving roughness element"—to the surface with a magnet inside the sphere, then moves the stud using an internal motor.

So why pursue it so doggedly? Because, McKeon says with a wry grin, "it's the only way I'll ever be able to beat my husband at golf."

EGG CARTONS AND AIRPLANES

She kids, mostly. What she finds out about controllable changes in roughness, she explains, will in the end likely be of more use to the aerospace industry than to the PGA. Which is just fine with McKeon—airplanes are the reason why she's at Caltech in the first place.

McKeon has been interested in aerodynamics since her childhood in Surrey, England, much of which she spent flying with her father, a flight engineer for British Airways. "I used to wonder how it was that I got to 30,000 feet in the air," she recalls, "as well as how it was that I stayed there."

In high school, she decided that she, too, wanted to fly jets—fast ones. "But at that time in the U.K.," she says, "women couldn't fly anything fast enough or exciting enough. So I decided to do the next best thing and design them." Learning to design airplanes, however, required a serious foray into the worlds of physics and engineering, of ailerons and flaps, of airfoils and fluid flow.

"I got sidetracked," she admits. "And I've never looked back."

Ironically, McKeon can't fly many of the vehicles her work impacts today, either. Not because they're off-limits to women, but because they're unmanned air vehicles, or UAVs—drones intended to fly into places too small or too hazardous for larger, manned vehicles. They're the sorts of vehicles used today, for instance, in Middle East war zones. "Our goal is to make them more agile and more maneuverable, and to design new means of controlling them that allow them to be lighter and more efficient," McKeon says.

These UAVs obey the same principles of aerodynamics as commercial aircraft, increasing lift by increasing the angle of attack—tilting their wings (or flaps) to create the needed pressure differential between the wing's top and bottom.

"Of course, if you tilt too far, the air can't follow the wing any more, and the layers separate," McKeon explains. "You lose lift and you get more drag, which can be a problem when you're trying to take off. In addition, these things—loss of lift, increase in drag—can lead to stalling in midair when you're trying to maneuver in the sky."

The solution? You could make sure not to overrotate the wing, for one thing. But in UAVs that travel at speeds much lower than those of their bigger commercial brethren, restricting rotation can significantly reduce maneuverability.

Instead, McKeon suggests changing the interaction between wing and air. "Low-speed UAVs operate at conditions very similar to where a golf ball's dimples have their biggest effect," she notes. In other words, the vehicles fall right in the sweet spot where you can push a flow to either stay laminar or become turbulent. The best way to give a UAV such a push, McKeon adds, would be with a wing material that can go from smooth to rough as needed during flight. Smart materials: they're not just for golf balls any more.

But how rough is rough enough—and how rough is too rough? After all, rough-

Right: A U.S. Air Force Global Hawk unmanned reconnaissance aircraft. Photo reproduced with permission of the Air Force.

Far Right: Decomposing an irregularly rough surface into a series of regular egg-carton shapes like this allows McKeon's group to find the optimum surface for a given application.

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ness can foul things up as easily as it can make them better. Just ask the U.S. Navy: a guided-missile frigate with a hull befouled by barnacles and marine slime can burn an extra three-quarters of a million dollars' worth of fuel a year.

Understanding the ways in which roughness affects turbulent flow is one of the things McKeon and her colleagues have been grappling with in the lab. And the best way to get a handle on roughness, they've found, is to turn sandpaper into egg cartons.

Sandpaper, the classic rough surface, has a wide, uneven range of peaks and troughs. Blow air over sandpaper and you'll get lots of disturbances in the flow—but it's nearly impossible to determine which peak is creating which disturbance, much less tease out whether that contribution is useful or detrimental.

Nearly. The way to make the impossible possible, McKeon says, is to simplify it—specifically, by turning it into a series of egg cartons. That's because egg cartons, with their characteristic uniform peaks and troughs, have easily measurable effects on any fluid flowing over them—effects that can be analyzed in great detail.

"Sandpaper is irregular," she explains, "but we can decompose it into linear combinations of simple, characteristic streamwise and spanwise wavelengths that, like egg cartons, are all very regular."

McKeon and crew have created a computer model of a dynamically morphing surface. The model can not only decompose a swatch of sandpaper into egg cartons, as she describes, but can pick out the carton that creates the biggest wavelike disturbance in the fluid's flow. And from knowledge springs control: "If we want to mitigate the effect of the sandpaper, we know we need to get rid of this particular wavelength," says McKeon. "If we want to enhance the sandpaper's effects, then that's the wavelength to use. We can predict which egg carton will give us our best response, and what that response will be."

And soon, perhaps, they can begin to slap those egg cartons—or, rather, the real-world versions of those egg cartons—onto the wings of a type of UAV known as a micro air vehicle, or MAV, to see if they're capable of replacing the flaps and ailerons of commercial aircraft.

"Because MAVs are tiny, insect-sized craft, it's not clear that it's best to use the same types of heavy mechanisms as in larger planes," McKeon notes. "Instead, you could imagine that if you had this sort of dynamic roughness on both wings, you could make one wing rough relative to the other. Instead of flaps and ailerons, you could use patches of roughness to tickle the flow over the wings, maneuvering the vehicles while keeping them light."

So this is where the flow of her still-early scientific career has carried Beverley McKeon: to huge, wind-and-water-blown tunnels; to collaborative treasure hunts for materials smarter than any created before; to palm-sized aircraft with the potential to dart and dash in ways previously thought impossible.

And to a vision of a golf ball that will let her best her husband in golf.

In the end, sometimes it really is the little, dimpled things that matter most. E&S

Beverley McKeon is assistant professor of aeronautics at Caltech. She did her undergraduate work at the University of Cambridge, where she also received a Master of Engineering degree. She got her PhD from Princeton University in 2003 for work on pipe flow, and after a Royal Society postdoctoral fellowship at Imperial College, London, she arrived at Caltech in 2006. At Caltech, she works at GALCIT as well as with the flow-control group in the newly created Center for Bioinspired Engineering.

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Kaushik Bhattacharya is the Tyson Professor of Mechanics and professor of materials science, as well as executive officer for mechanical and civil engineering.

Michael Ortiz is the Hayman Professor of Aeronautics and Mechanical Engineering.