Broken symmetry inside ovens

by Bruno van Wavenburg

When you take a symmetrical oven and simulate the airflow inside it, you expect that it will be symmetrical as well, or at least that any lack of symmetry will eventually level off. However, Applied Physics researchers Luuk Thielen and Leon Geers found that this was far from the truth when they discovered a persistent vortex on one side of an oven. It was first discovered in Thielen’s computer simulations, and later it also showed up in Geers’ experimental set-up.

One thing should be made perfectly clear: it is far too early yet to talk about the “hot cake” effect, or the “Thielen-Geers vortex”. Nonetheless, doctorate students Luuk Thielen and Leon Geers of the Thermal & Fluids Sciences Section at the Applied Physics department did bump into a very strange phenomenon indeed during their research into airflows inside baking ovens.

‘Other scientists at conferences are reluctant to believe us,’ Geers says. They discovered the highly unusual vortex in their highly-stylised version of a hot-air baking oven. Even though the oven is exactly symmetrical, the vortex occurs on one side of the oven only. This is not how it should be, according to Thielen,
who first detected the phenomenon during a computer simulation. ‘My immediate reaction was that it had to be a bug in the program code.’

**Pizzas** Their interest in baking ovens goes back about four years, when the Rademaker Den Boer company, manufacturers of baking ovens, approached the research establishment TNO/TPD in Delft for advice and were referred to Delft University. They wanted to know whether there wasn’t a more scientific way of fine-tuning their most popular models. ‘These are ovens for any number of baked products, including bread, pizzas, cakes and what have you,’ Geers explains. A conveyor belt carries the products through the oven’s two chambers where hot air is blown onto the food through hundreds of nozzles. ‘This is called the impinging jet principle,’ Geers explains. ‘It is a highly efficient method of transferring heat.’ However, it can take as much as a couple of weeks to find the correct settings—pressure, temperature, distance between the jet nozzles—for a new oven. According to the researchers most of the work is still done by trial and error, which works well enough, but the manufacturer wondered whether there might be a quicker or more efficient way to find the settings.

**Volume elements** One thing led to another, and the researchers have now been working on the project for four years. It is being co-financed by STW, the Netherlands Technology Foundation, as part of research into airflows inside baking ovens. There’s enough science in it to keep the Delft researchers occupied for a while yet. One of the problems that inevitably crops up is turbulence, the wild, unpredictable flow phenomenon that was once called the trickiest problem in all of physics. ‘The air flow is described by the Navier-Stokes equation,’ Thielen starts to explain. ‘Now this is a relatively simple-looking formula that describes how the velocity, direction, and density of the flow changes in each volume element at any given moment in time.’ Solving the equation is a different matter, and requires the use of a computer. To give the computer something to work on, one has to cut up the virtual baking oven into a number of volume elements, and divide time into small intervals. As the time and space intervals become smaller, the accuracy of the simulation increases, but so does the calculation time. Thielen uses hundreds of thousands of such elements, but he used a simplified model for his virtual baking oven featuring a virtual plate with nine instead of hundreds of holes in a square pattern. The air is blown downwards through the holes. ‘The pattern being symmetrical, you would expect the four jets on the sides and the four jets on the corners to be identical,’ Thielen says.

**Vortex** The original Rademaker oven featured a different, triangular pattern, but the square pattern proved to be easier to generate using the simulation software. ‘If I had not changed the pattern, we would never have found the effect,’ Thielen says. As it was, the behaviour of the virtual flow wasn’t even close to what was expected. In the graphs produced by Thielen’s computer program (in which, to simplify matters, only one quarter of the nine-nozzle plate is shown) one of the two side jets is blown off course by a small vortex. However, the corresponding column of air diagonally across the plate shows no movement at all. In a view closer to the impingement surface, the asymmetrical vortex can even be seen to one side of the diagonal as a small, convoluted hurricane in the jumble of lines. ‘This was very strange, and when after several weeks I still hadn’t managed to find a bug in the code, I began to believe something else was going on,’ Thielen recalls. One option would have been to change the computer model. ‘The problem with turbulence is that the vortices also appear in space and time scales smaller than the ones you are looking at,’ Thielen explains. ‘This means that you have to make assumptions about the average effect of the smaller scales, in the form of a turbulence model. There are simple and more complex models, but none of them is perfect.’ Even when Thielen opted for a different turbulence model, the asymmetry persisted.

**Experiment** It was about time to look for experimental evidence. This was done by Leon Geers in a test rig that looks a bit like a kitchen extractor hood located in the centre of a basement of the Applied Physics building. A fan extracts air from the room through a hose as thick as a man’s arm, and blows it through a grille. Geers indicates how the air flows thus produced hit a piece of metal film stretched below the hood.
An electric current flowing through the metal film heats it to a temperature of about 40 °C. At the same time the film is cooled by the jets of air striking it, which are at room temperature. This is exactly the opposite of what happens inside an oven where hot jets of air hit cold pizzas.

‘Physically speaking, the processes are identical,’ the researcher explains, ‘or rather, mutatis mutandis, the equations that apply to the former situation also apply to the latter.’

The bottom side of the metal film is coated with temperature-sensitive liquid crystals like the ones used in baby baths that change colour as they heat up or cool down. Geers uses these to measure the transfer of heat from the film to the jets. In order to map the flow itself, he creates a fog of minute droplets of a glycerol/water mixture that is injected into the airflow. A laser stroboscope is then used to capture the result on video. For each exposure, two laser pulses with an interval of a few microseconds illuminate the droplets in a plane.

During the short interval, each droplet will have moved slightly, and the movement of the airflow can be readily deduced from the video recordings.

According to Geers the measuring technique is far from easy, since the results include quite a bit of noise.

‘A single velocity field image takes three thousand exposures that have to be averaged to remove the noise.’

Car windscreens The efforts paid off in the end, since the experimental set-up also showed the vortex on one side. ‘Once you get the same results from calculations and from experiments, you have a strong case,’ Geers says. ‘Later, at a conference, we found out that others had observed similar phenomena, but under different conditions and only at limited velocities. This phenomenon had never been discovered in impinging jet flows.’

Whatever the case the effect is not going to set the cash registers ringing for the oven manufacturers. For one thing, Geers suspects that the transfer of heat will not be greatly affected by the vortex. On the other hand, researchers need to constantly update their knowledge of flows if they are to improve the models they use, and this certainly is an unexpected new element that requires study.

What’s more the models are of use to others besides oven manufacturers. Jets of air are also used to cool the hot glass of newly-produced car windscreens and the hot metal surfaces of large ball bearings. Even turbine blades in aircraft engines are cooled by them from inside. These are all high-tech applications in which the smallest improvement in efficiency could result in massive cost savings.

However, Geers and Thielen are making no promises.

‘For the time being the only ones who can enjoy this will be scientists,’ Thielen says. ‘Asymmetrical phenomena like these are known in the field of physics as «symmetry breakings». The vortex «breaks» the initial symmetry by moving to one side of the grid.’

Whatever the case giving the phenomenon a name does not provide an explanation for it.

‘Lots of possible explanations exist but each of them can be refuted in one way or another. We have enough questions to keep us going for the next decade,’ says Geers, who, like Thielen, recently gained his doctorate, and who likes to think that his successors will continue the work. Which is why they think it is still too early to stick a label on the effect. Putting forward your own name is out of the question in scientific circles, but even so Thielen thinks that perhaps his successors will continue the work. Which is why they think it is rather, mutatis mutandis, the equations that apply to the former situation also apply to the latter.’

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For numerical simulations a grid generator is used to first prepare a calculation grid consisting of small cells. The grid is then used to solve the flow equations by means of a finite volume program called X-stream, which has been developed by TNO/TPD. In view of the symmetrical layout of the set-up only one quarter (i.e., 2x2) needs to be considered.
Calculations made with X-stream showed that one of the four airflows in the square matrix (the one at 12 o’clock) was being pulled out of line. Further research showed that the effect was being caused by an unusual vortex. Intuition suggests that the system should be symmetrical along the diagonal.

Data obtained by measuring the airflows from a 2x2 matrix confirm the existence of the special vortex, as shown by this visualisation.

A different representation of the same simulations was made using the AVS program to show the unusual vortex better. The view of this plain shows a situation parallel to the metal film and one-tenth of a millimetre above it. When Thielen brought the vortex to the attention of the audience during his presentation at an international conference, the response was sceptical. During informal meetings later on, several people admitted having seen something similar, albeit under different conditions and at lower velocities.