////Title: Simulating Supersonic Fluid Flows in the Student Aerodynamics Lab

////Standfirst:

When learning about fluid dynamics, physics and engineering students can benefit greatly from hands-on experiments that allow them to visualise the equations they learn in lectures. For supersonic flows, however, the equipment required is incredibly expensive, making some experiments inaccessible to many universities. Dr Oleg Goushcha (Oh-leg Goo-shah) at Manhattan College has revived an old methodology to demonstrate supersonic flows in the classroom using far more affordable equipment. He has shown that the features seen in supersonic can be accurately simulated through an inexpensive setup involving water surface waves.

////Main text:

Fluid dynamics is a highly complex field in physics. Describing how liquids and gases behave as they move around and interact with each other – as well as with solid bodies – requires a diverse array of equations, which are difficult for non-experts to comprehend. All the same, an engrained understanding of these behaviours is critical for many engineering applications, including aerodynamics, aircraft design, propulsion, and flight dynamics. As they grasp these concepts, students can greatly benefit from hands-on experiments that help them to explore the physical consequences of the equations they have learnt.

Unfortunately, the equipment needed to demonstrate supersonic flows, in which fluid is moving faster than the speed of sound, is costly. Such supersonic flows can only be created in the lab inside supersonic wind tunnels, which are prohibitively expensive for most learning institutions. However, Dr Oleg Goushcha at Manhattan College aims to prove that such inaccessible equipment is not always necessary for these experiments. In fact, he has found that the same results can be simulated with relative accuracy using far cheaper equipment.

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As a flowing gas interacts with a solid object, waves can form that compress the fluid in characteristic patterns, and can be accurately described using mathematical equations. Unlike gas, water cannot be compressed in the same way when pressure is applied, but a comparable effect can be seen in shallow water flowing across a surface. When an obstacle is placed in the way of the flow, the heights of the resulting water waves are directly comparable with the degrees of compression experienced by a flowing gas.

To exploit these comparable behaviours, Dr Goushcha has used a ‘water table’ device, in which a water reservoir drains through a narrow channel onto a flat, transparent testing section. When using this device, a student can easily tune the flow rate and channel width. Additionally, a wave-triggered lighting arrangement, combined with a pattern placed under the table that appears distorted by waves, allows the student to accurately quantify the wave patterns.

In two separate papers, both published in the *International Journal of Mechanical Engineering Education*, Dr Goushcha describes two different experiments of supersonic fluid dynamics made possible with this setup that he uses in his classes.

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In the first paper, Dr Goushcha used the water table to simulate Laval (Lah-vaul – 'vaul' is the stressed syllable) nozzle flow. Used in most rocket engines today, these structures are cylinders that have been pinched halfway down to create an uneven hourglass shape. By converting heat to kinetic energy, a Laval nozzle can accelerate hot, pressurised gases to supersonic speeds. To characterise these flows, engineers use a value named the 'Mach (Mack) number' to describe the velocity of the gas exiting the pinched 'throat' of the nozzle. When designing these structures, they must carefully consider how throat areas should be optimised to maximise Mach numbers.

By revisiting the mathematics that describes this process, Dr Goushcha has identified an equation that allows students to calculate theoretical values for Mach numbers from the measured water depth in the water table. This provided the basis for an experiment in which his students varied the width of the channel in the device, and then measured how the downstream wave heights changed in turn. From these measurements, they could then calculate robust theoretical relationships between the throat width of a Laval nozzle, and the corresponding Mach number of the exiting gas.

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In his second paper, Dr Goushcha describes how the same water can be used to study 'oblique shocks', in which gas compression waves are inclined with respect to the overall direction of the flow. They occur when a wedge is placed in the path of a supersonic gas and are particularly important for engineers to consider when designing geometries of a supersonic aircraft: if their shapes are not just right, the flow speeds and directions can be off-target, lowering the airplane's efficiency.

Dr Goushcha devised an experiment imitating this effect, where wedges of different sharpness are placed in the testing area of the water table. As with oblique shocks, the deflection angles of the resulting water waves are strongly dependent on the sharpness of the wedge, and can be easily visualised with the water table. For this situation, Dr Goushcha identified a mathematical link between the wave deflection angles that emerge from the setup, and the degrees of compression in real oblique shocks.

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When conducting each of the two experiments, Dr Goushcha's students gathered their values for wave shapes and formed angles by capturing images of the water flow on their smartphones, and then uploading them to a computer for analysis. They then applied these results to the equations provided by Dr Goushcha for both experiments, to calculate theoretical values for throat width-dependent Mach numbers and wedge sharpness-dependent deflection angles. Finally, the students compared their theoretical values with experimental measurements made using wind tunnels, which allow compression waves to be observed directly.

For the Laval nozzle experiment, the theoretical and experimental values came within 10% of each other. A similar value emerged for the deflection angles in the second experiment – though accuracy deteriorated somewhat for blunter wedges. Ultimately, both water table experiments were clearly analogous to real-world situations, such as gas being propelled from a rocket engine, or the body of a supersonic jet cutting through air.

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The values gathered by Dr Goushcha's students were more than sufficient to accurately convey some important principles of fluid dynamics. To quantify the success of the experiments, Dr Goushcha asked his students to complete a survey, asking them if they agreed or disagreed with three statements: the experiment enabled them to better understand compressible flow theory; the water table was a good visual aid; and the lab experiment was a useful part of the course.

Encouragingly, 93% of the students agreed with all three statements – presenting a strong case for the wider use of the water table in both undergraduate and graduate-level fluid dynamics courses. Ultimately, the equipment could benefit many students who are currently placed at a disadvantage in their education, due to the limited budgets of their institutions.

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This SciPod is a summary of the papers 'Revival of water table experiments in fluid mechanics courses, part I' and 'Revival of water table experiment in fluid mechanics courses, part II', from the *International Journal of Mechanical Engineering Education*.
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