Textbook formulas for describing heat flow characteristics, crucial in many industries, are oversimplified, study shows

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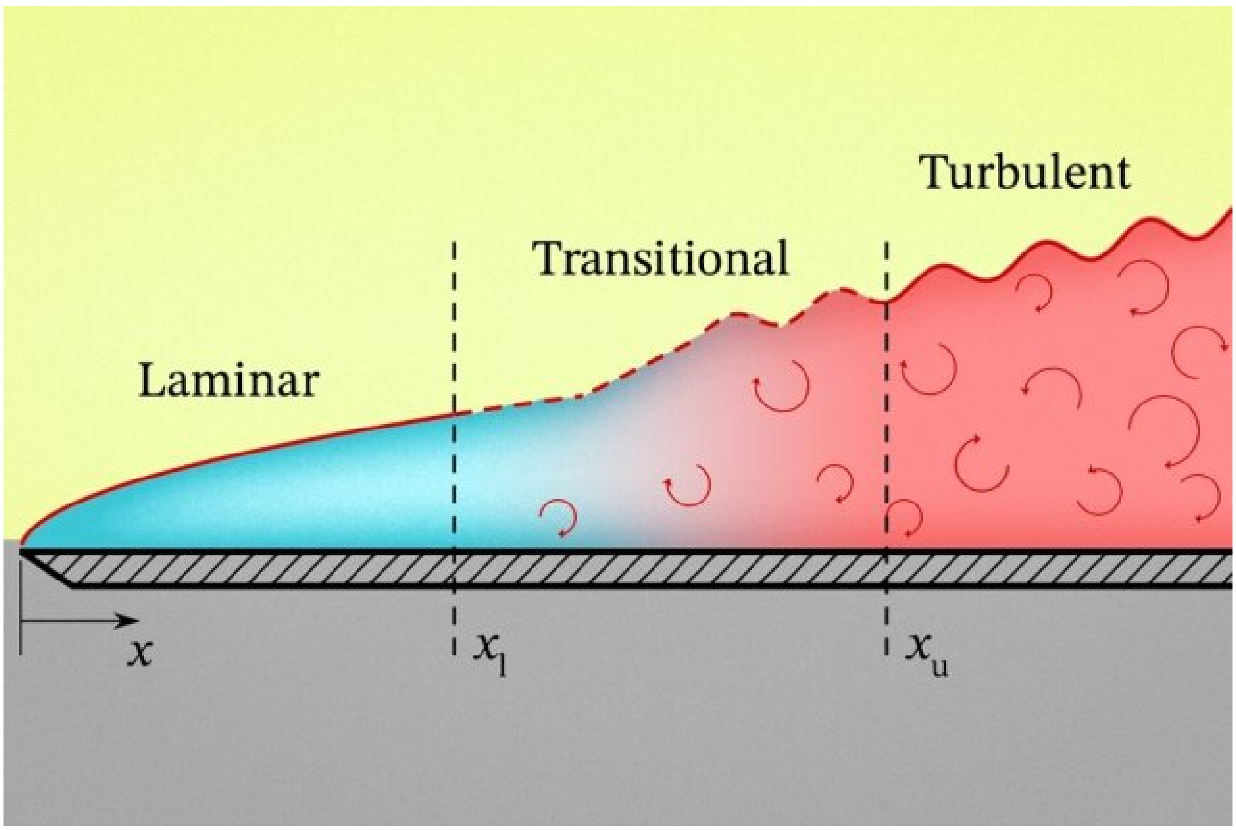

Fluids that heat or cool surfaces make a transition from a smooth flow to a mixing, turbulent flow. A new MIT analysis shows the importance of the transition region to heat flow and temperature control. Credit: Courtesy of the researchers, edited by MIT News

Whether it's water flowing across a condenser plate in an industrial plant, or air whooshing through heating and cooling ducts, the flow of fluid across flat surfaces is a phenomenon at the heart of many of the processes of modern life. Yet, aspects of this process have been poorly understood, and some have been taught incorrectly to generations of engineering students, a new analysis shows.

The study examined several decades of published research and analysis on fluid flows. It found that, while most undergraduate textbooks and classroom instruction in heat transfer describe such flow as having two different zones separated by an abrupt transition, in fact there are three distinct zones. A lengthy transitional zone is just as significant as the first and final zones, the researchers say.

The discrepancy has to do with the shift between two different ways that fluids can flow. When water or air starts to flow along a flat, solid sheet, a thin boundary layer forms. Within this layer, the part closest to the surface barely moves at all because of friction, the part just above that flows a little faster, and so on, until a point where it is moving at the full speed of the original flow. This steady, gradual increase in speed across a thin boundary layer is called laminar flow. But further downsteam, the flow changes, breaking up into the chaotic whirls and eddies known as turbulent flow.

The properties of this boundary layer determine how well the fluid can transfer heat, which is key to many cooling processes such as for high-performance computers, desalination plants, or power plant condensers.

Students have been taught to calculate the characteristics of such flows as if there was a sudden change from laminar flow to turbulent flow. But John Lienhard, the Abdul Lateef Jameel Professor of Water and of mechanical engineering at MIT, made a careful analysis of published experimental data and found that this picture ignores an important part of the process. The findings were just published in the *Journal of Heat Transfer*.

Lienhard's review of heat transfer data reveals a significant transition zone between the laminar and turbulent flows. This transition zone's resistance to heat flow varies gradually between those of the two other zones, and the zone is just as long and distinctive as the laminar flow zone that precedes it.

The findings could potentially have implications for everything from the design of heat exchangers for desalination or other industrial scale processes, to understanding the flow of air through jet engines, Lienhard says.

In fact, though, most engineers working on such systems understand the existence of a long transition zone, even if it's not in the undergraduate textbooks, Lienhard notes. Now, by clarifying and quantifying the transition, this study will help to bring theory and teaching into line with real-world engineering practice. "The notion of an abrupt transition has been ingrained in heat transfer textbooks and classrooms for the past 60 or 70 years," he says.

The basic formulas for understanding flow along a flat surface are the fundamental underpinnings for all of the more complex flow situations such as airflow over a curved airplane wing or turbine blade, or for cooling space vehicles as they reenter the atmosphere. "The flat surface is the starting point for understanding how any of those things work," Lienhard says.

The theory for flat surfaces was set out by the German researcher Ernst Pohlhausen in 1921. But even so, "lab experiments usually didn't match the boundary conditions assumed by the theory. A laboratory plate might have a rounded edge or a nonuniform temperature, so investigators in the

1940s, 50s, and 60s often 'adjusted' their data to force agreement with this theory," he says. Discrepancies between otherwise good data and this theory also led to heated disagreements among specialists in the heat transfer literature.

Lienhard found that researchers with the British Air Ministry had identified and partially solved the problem of nonuniform surface temperatures in 1931. "But they weren't able to fully solve the equation they derived," he says. "That had to wait until digital computers could be used, starting in 1949." Meanwhile, the arguments between specialists simmered on.

Lienhard says that he decided to take a look at the experimental basis for the equations that were being taught, realizing that researchers have known for decades that the transition played a significant role. "I wanted to plot data with these equations. That way, students could see how well the equations did or didn't work," he said. "I looked at the experimental literature all the way back to 1930. Collecting these data made something very clear: What we were teaching was terribly oversimplified." And the discrepancy in the description of fluid flow meant that calculations of heat transfer were sometimes off.

Now, with this new analysis, engineers and students will be able to calculate temperature and heat flow accurately across a very wide range of flow conditions and fluids, Lienhard says.

More information: John H. Lienhard, Heat Transfer in Flat-Plate Boundary Layers: A Correlation for Laminar, Transitional, and Turbulent Flow, *Journal of Heat Transfer* (2020). DOI: 10.1115/1.4046795

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