Science versus Schools of Thought in Fluid Dynamics

Adam B. Suppes and Galen J. Suppes

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Basic explanations of how air flow responds to surfaces and restrictions (aka Venturi effect) are in error based on computational fluid dynamic (CFD) simulation results. A correct explanation is consistent in both molecular and continuum mechanics and extrapolates accurately toward innovation to high-impact applications.

Introduction - A key derivation at the onset of chemical engineering education is the Bernoulli equation as a simplified version of the energy balance equation. This basic derivation tends to be extrapolated to a range of applications including the Venturi meter and theories of flight. While the energy balance may hold in some applications, such as closed systems, errors in application lead to errors in quantifying physical properties for the most basic of objects.

For flow through an elbow in a pipe, a key transformation is the manner in which the fluid interacts with the wall to generate pressure. That pressure causes flow to change direction. Fundamentally two phenomena emerge. First, at the molecular level, interaction with the wall creates a pressure. Secondly, and especially for gas phases, higher pressures expand at the speed of sound to impact flow and pressures over significant distances.

Accurate explanations based on physics and the molecular theory of gases can be accurately applied to a range of common objects such as flow through pipe elbows, the Venturi meter, the generation of air flow in chimneys, how air flow creates aerodynamic lift, and the aerodynamics behind hovercraft. This paper uses CFD simulation solutions of air flow around digital prototypes as a basis for understanding the fundamental physics. The results are verified by a consistency of molecular mechanism, continuum mechanics, and accurate extrapolation of performance.

Background - While both fluid dynamics and thermodynamics are core sciences upon which chemical, mechanical, and aerospace engineering are founded, they are considerably different in their rigor. Much of thermodynamics is devoted to fundamentals upon which reversible processes (e.g., heat engines) are developed to identify the best possible performances and deviations from ideal behavior; this foundation culminates in available energy and lost work analyses which help identify where inefficiencies occur. A similar precision does not exist in fluid dynamics.

A Feb-2020 article summarizes the dubious foundation of fluid dynamics in text and in its title, "No One Can Explain Why Planes Stay in the Air [1]." Closer to home for chemical engineers is the question:

Why does a gas flow in a pipe follow the sweep of the pipe's elbow?

A common school of thought in aerospace engineering is that a flow follows a curved surface due to the "Coanda Effect" as illustrated by Figure 1. While it is common for laminar flow regimes to follow the curvature of a surface, it is not a fundamental phenomenon. The Coanda Effect is attributed to the fluid sticking to the surface; however, air has little tendency to stick to or adsorb to solids.

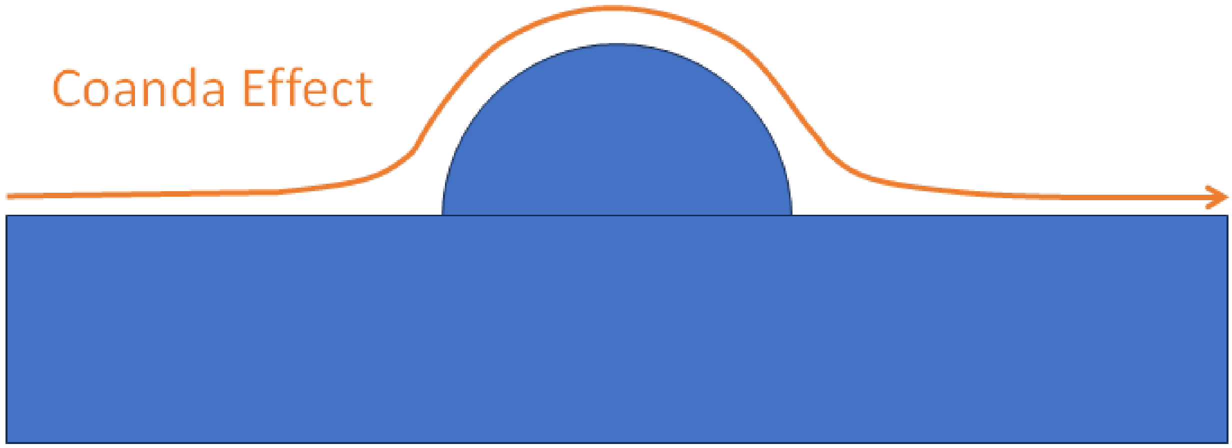


Figure 1. Illustration of Coada Effect where fluid is said to stick to and follow the surface.

Computational fluid dynamics (CFD) has evolved separate from the simple-explanation schools of thought, and in the evolution of CFD, CFD's simulation results are both accurate and insightful [2, 3]. Figure 2 illustrates the CFD pressure profile for flow through the sweeps of two pipe elbows.

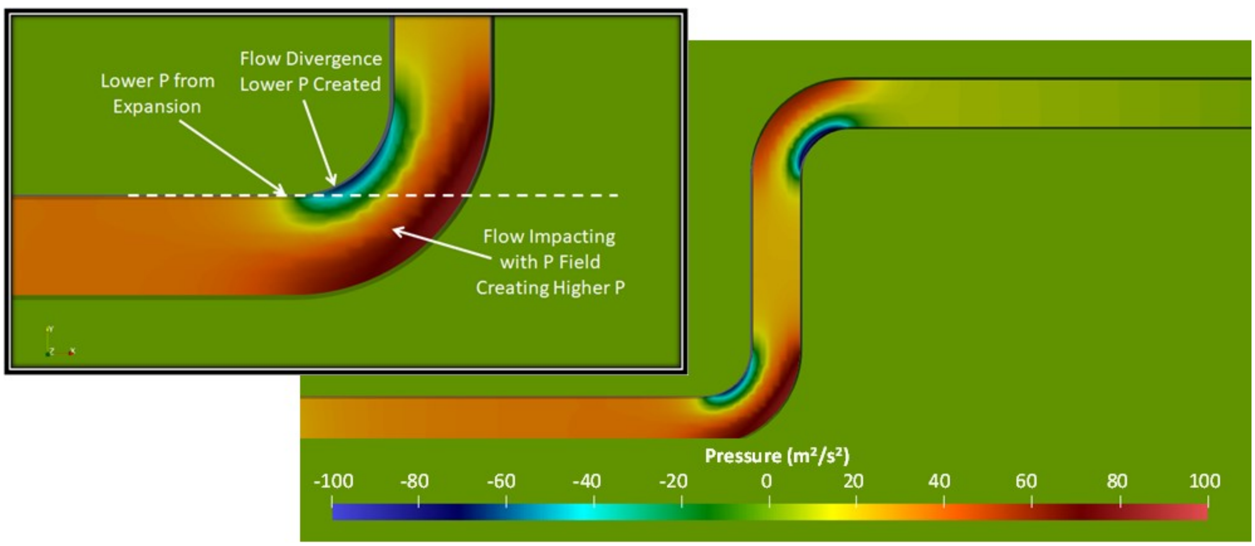


Figure 2. Pressure profile of flow around a pipe. Air flows from left to right at average speed of 10 m/s.

The fundamental driving force for the flow dynamics is described by three principles:

1. Impacting air creates higher pressures such as along the sweep's outer radii.
2. Diverging air creates lower pressures such as along the sweep's inner radii.
3. Air expands from higher to lower pressure at the speed of sound such as the lower and higher pressures forward the sweeps.

The expanded insert of Figure 2 identifies the portion of the surface where diverging flow generates lower pressures in addition to the section forward of the sweep where lower pressures are due to air expanding into the lower pressure region created by diverging flow.

The airfoil pressure profiles of the airfoils of Figure 3 illustrate the same phenomena. The airfoils are flat plates with rounded leading edges. The upper airfoil has a vertically symmetric taper while the lower airfoil has a taper extending from the upper surface to a trailing edge on the lower surface. The pressure profiles are explained by the same three basic physical phenomena:

1. Impacting air creates higher pressures which are illustrated by the higher pressures at leading and trailing edges.
2. Diverging air creates lower pressures which is a case for the four (a) or three (b) blue areas.
3. Air expands from higher to lower pressure at the speed of sound which is why a change in the airfoil's trailing taper impacts the pressure throughout the airfoil.

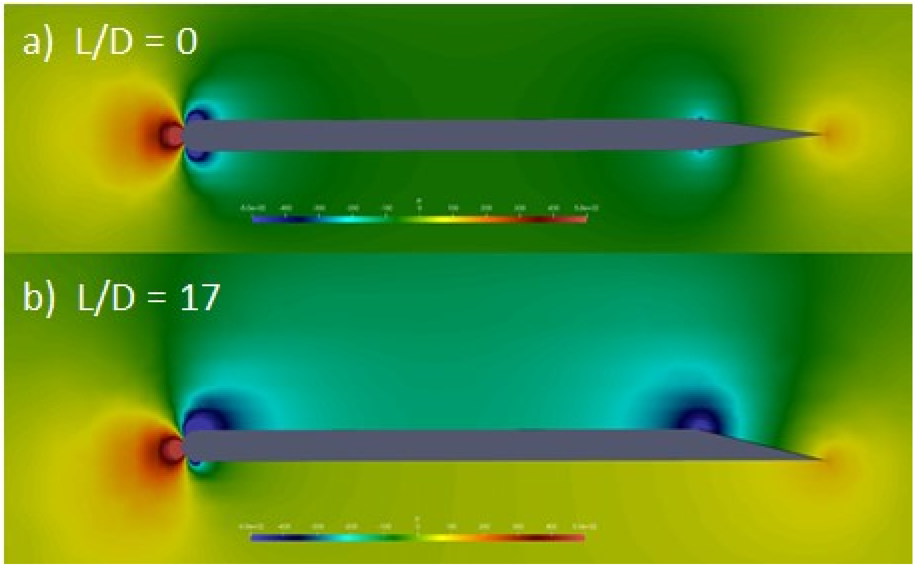


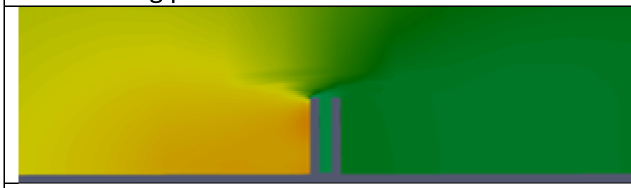
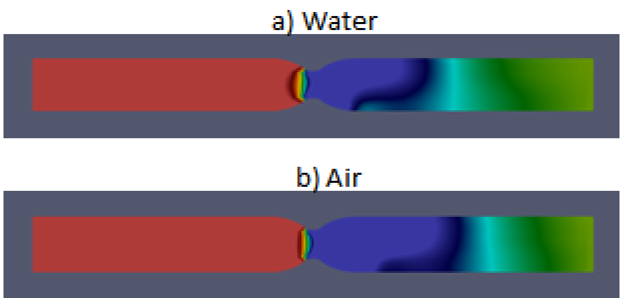
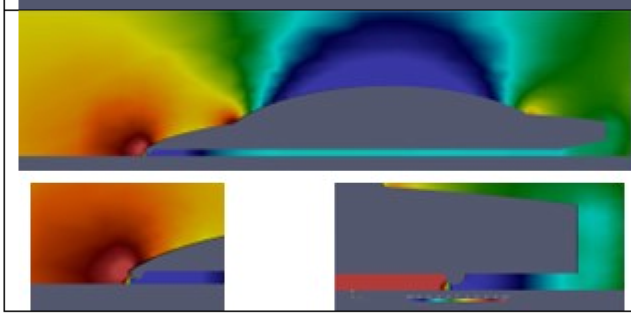
Figure 3. Illustrative example of how a change in shape at a trailing edge impacts the 2D pressure profile throughout an object due to pressure propagating at the speed of sound. Red is higher pressure and blue is lower pressure; both are pressures relative to the surroundings. Air flows from left to right at average speed of 40 m/s.

The pressure fields surrounding the airfoils form in a pseudo-sequence of: a) air flow impacts the leading edge to form higher pressures, b) oncoming air flow impacts the leading-edge higher pressures where the resultant flow vectors flow away from the leading edge curvature to leading to lower pressures above and below the airfoil behind the leading edge, c) flow becomes increasingly parallel to the upper and lower surfaces unto they diverge from the trailing tapers where lower pressures emerge, d) flows parallel to the surfaces collide immediately behind the trailing edge to form higher pressures, and e) the flow evolves to a steady-state pressure field due to expansion from higher to lower pressures throughout the airfoil's surface. For the steady-state pressure field, the impacts in front of the leading edge includes flow both impacting the higher-pressure air and the surface where the amount of "flow" that actually reaches the surfaces may be considerably less than the amount of flow that collides with the pressure profile to achieve the steady-state pressure profile, creating the boundary layer.

At the molecular level, pressure expands in every direction from the surface in a random distribution of molecular vectors from the surface. The air flow relative to an airfoil moving toward the air comprises molecules of random velocity vectors to which the relative velocity vector of the airfoil's velocity is added.

Common Examples – Table 1 summarizes three examples of how the Three Principles explain the air flow mechanisms behind these widely-used devices. Chimneys are often erroneously described has having upward air flow due to the Venturi Effect when they are example of diverging air flow above the duct that creates a lower pressure that pulls air up through the chimney.

Table 1. Examples of common devices with expression of the Three Principles in the pressure profiles. All pressure profiles are in scale of red (high), lime-green (zero), and blue (low) pressures relative to surrounding pressures.

	**a) Chimney** - Generation of higher pressure on the windy side of the chimney causes diverging air flow above the duct exit. Diverging air creates lower pressure suction.
	**b) Venturi Meter** – Classic explanations of the Venturi Meter consist of the restriction causing higher velocity and the higher velocity creating lower pressure in the restriction. If that explanation were correct, the pressure of fluid after the restriction would be similar to the pressure before the restriction. The three principles accurately describe the pressures.
	**c) Sportscar Racecar** – Race cars use a front (lower) spoiler to create suction under the car to increase traction for steering and acceleration. The spoiler works like the upper half of the Venturi Meter, not to be confused with the "Venturi Effect" which is erroneous. Moving the spoiler (bump) rearward causes higher pressures under the underbody.

The Venturi Meter is a topic of course content and experiments throughout engineering and the sciences; it is so widely recognized that the observed generation of lower pressure is referred to as the Venturi Effect. While the meter consistently generates a lower pressure at the meter's restriction, the common explanation of how higher velocities create lower pressures in the restriction is in error. Diverging air flow at the restriction is the cause of lower pressures. If the meter were substantially a tradeoff between energy stored as velocity versus pressure, the pressure before and after the restriction would be similar; and also, there would be a steady decrease in pressure as the diameter reduces on approach to the minimum diameter. Impacting air related to the decreasing diameter creates higher pressures which cause diverging air and lower pressures in the restriction.

When air enters at an opening to the surroundings, such as a front spoiler, the higher pressures reach the opening (at the speed of sound) and partially divert air flow from entering the space. This restriction of air flow is the primary cause of lower pressures behind the restriction/spoiler which pulls down on a racecar to create improved traction. If the restriction is moved rearward on a car, higher pressures generate aerodynamic lift on a car.

Bernoulli's Equation – Bernoulli's equation is a simplified version of the energy balance. The previous examples illustrate how the forces resulting from the translation and momentum of molecules interact with surfaces to create pressures which change the direction of fluid flow. The direction of fluid flow relative to a surface determines if the flowing molecules have greater tendency to impact a subsequent surface or to diverge from the surface's curvature to create to lower density of the molecules in the "shadow" of the flow relative to the surface. Bernoulli's equation fails to take into account two factors which dominate the formation of pressure fields along objects: 1) it fails to account for formation of higher and lower pressures due to interaction with surfaces and 2) it fails to take into account how pressure expands at the speed of sound.

The "Bernoulli Theory of Lift" fails to take into account force balances with surfaces and how pressure expands at the speed of sound. The application of Bernoulli's equation wrongly identifies that changes in velocity cause changes in pressure, while the fundamentally correct explanation is that pressure fields cause changes in velocity.

Similar erroneous explanations attribute pressures to be a result of air turning near surfaces, when the fundamentally correct explanation is that pressure fields effectively turn air's flow.

Similar erroneous explanations apply Bernoulli's equation to explain how a Venturi Meter works. A careful inspection of the pressure profile of a Venturi Meter reveals that lower pressures form only when the surface near the restriction diverges away from the flow. Initial restrictions in diameter of a Venturi Meter result in higher pressures rather than lower pressures; impacting flow overrides higher velocities to create higher pressures rather than lower pressures until the flow diverges from the surface.

As illustrated by Table 1, the pressure forward of the restriction of a Venturi Meter is higher than after the restriction. The spoiler below the leading edge of a race car exhibits similar behavior as the Venturi Meter of Table 1. Higher pressure develops forward the spoiler, and that higher pressure causes reductions in the amount of flow going under the car. After the bump, the combination of: a) flow diverging from the surface, b) a reduced air flow due to more flow proceeding over the hood, and c) a fixed flow expanding to a larger cross section cause lower pressures behind the spoiler. These lower pressures create a suction on the car underbody which increases traction for acceleration and steering which is a strategic design feature for race cars.

Global Understanding versus Memorizing Analogies – An approach to aerodynamics based on memorizing analogies like the Coanda Effect and Venturi Effect is limited in utility for novel design and innovation. However, accurate fundamentals extrapolate to new designs and innovations. The Three Principles are justified based on molecular mechanics [4-7]. CFD is based on continuum mechanics. The explanations provided in this work are accurate at the molecular mechanics level, the continuum mechanics level, and in extrapolation. Two examples of extrapolation are the ground-effect flight transit (GEFT) and the Bernoulli Loops of Figures 4 and 5.

Conceptionally, the innovations of Figure 4 and 5 are extrapolations of the Three Principles. When CFD results verified anticipated performances, the extrapolations were considered as accurate and viable.

The GEFT of Figure 3 is like a hovercraft; however, instead of blowers forcing air into a lower cavity, GEFT is designed to use air's oncoming air flow to maintain the lower cavity lift pressures. The trailing-edge flap of GEFT has pressure patterns similar to the spoiler of the Table 1 racecar, only the restriction is placed at the rear of the underbody and higher pressures expand forward from that trailing flap in the cavity. The lift pressures are substantially a free "bonus" resulting from a design that reduces aerodynamic drag. A significant advantage of "free" lift is that a 95% reduction in wheel-based suspension leads to a 95% reduction in rolling/mechanical losses. For streamlined trucks, cars, and trains; rolling losses can be as high as aerodynamic losses. This approach leads to major reductions in energy consumption which can lead to electric-powered trucks and a significant expansion on what is possible with direct solar powering of cars, trucks, and railcars.

The Bernoulli loops of Figure 4 use entrance and exit velocities from tunnel sections to reduce pressures within the tunnels. Whereas the typical Hyperloop concept is as tunnels isolated from surrounding railway infrastructure, the Bernoulli tube enable open entrances and exits where the tunnel transit corridors have lower pressures and perpetual tailwinds. Bernoulli Loops enable incremental railway extensions or modifications of existing tunnels to achieve Hyperloop corridors within a few years; The engineering feat becomes a design artifact rather than a research and development project.

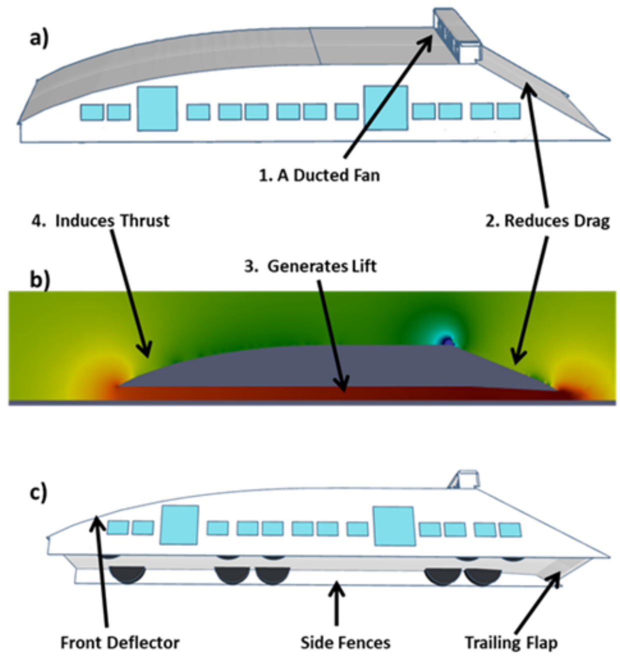


Figure 3. The ground-effect flight transit (GEFT) platform.

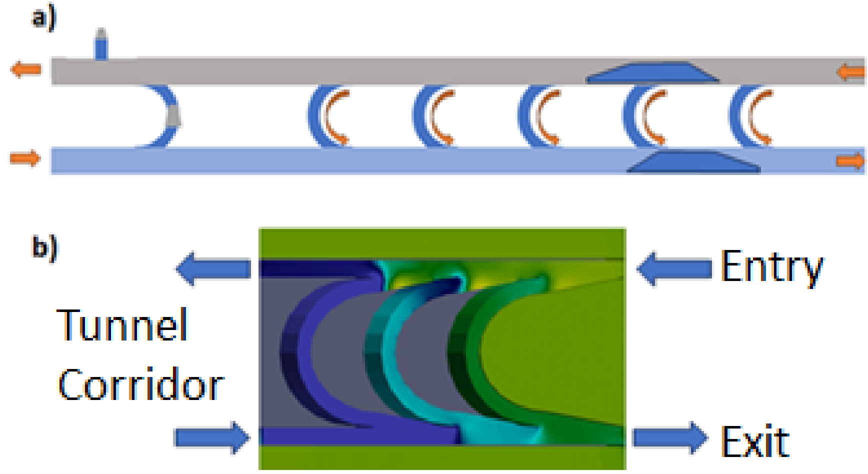


Figure 4. Bernoulli Loops for open-entry hyperloop tunnels.

Lost Work Analysis – Common sources of lost work for the vehicles (i.e., race car, GEFT, and aircraft with wings) of this paper include:

- Viscous drag rapidly dissipates to thermal energy waste; viscous drag is typically less than one fifth the drag for vehicles; it can primarily be kept low by avoiding turbulence.
- Boundary layer separation increases viscous drag; however, of greater detriment is the loss of lift with aircraft stall which is an artifact of turbulence expediting dissipation of favorable pressure profiles,
- Dissipation of pressure profiles occurs in both turbulent and laminar flow; forward dissipation is somewhat recovered; rearward dissipation is primarily lost toward generation of turbulence and vortices; lateral dissipation can be partially blocked by fences and winglets; downward dissipation is blocked by the ground in ground-effect leading to

increased lift and reduced drag; vertical dissipation can be blocked in tunnels leading to increased lift and the potential for reduced drag.

- Jet washes are streams of higher velocity air stratified with lower velocity air streamlines behind a vehicle which, when left unchecked, reduce to thermal energy loss; surface shapes and operating conditions impact jet wash.

These lost work artifacts are analogous to archeological artifacts that provide evidence as to what happened; but in addition, these artifacts point towards design and operational features which can be changed to reduce lost work.

As a result of deriving the Three Principles, ground effect flight was explored as a path of innovation. Initial work identified that railway tracks in combination with lower-cavity fences/skirts are a good approach to block lateral dissipation while benefiting from the ground blocking downward dissipation. While race car skirts are commonly used to block dissipation of undercarriage suction pressures, the use of air's dynamic pressure to sustain higher pressures below an undercarriage, including high synergy with railway tracks, represents a new path of innovation and critical thinking [8].

Table 2 and Figure 5 compare GEFT performance over ground and in a tunnel. The velocity profiles of Figure 5 illustrate the jet wash of initial simulations of GEFT in a tunnel. Performance in tunnels should have both greater lift and lift-drag rations (L/D) versus ground-effect. Greater lift was achieved, but lower drag was not achieved. The increased drag correlates with jet wash in the tunnel which manifests as drag due to the lower pressures behind the vehicle acting on the rear vehicle surface. Figure 5 is a version of lost work analysis which points towards vehicle surface modifications and ducted-fan utilization to reduce jet wash to reduce drag and increase overall efficiency in the tunnel.

TABLE 2.

SUMMARY OF 2D SIMULATIONS P-S. $C_{D,V}$ IS THE PERCENT OF TOTAL DRAG WHICH IS VISCOUS DRAG. THE UNITS ARE AS PROVIDED FOR SIMFLOW INPUT.

	$S(m^4/s^2)$	L/D	Cl	Cd	Cd,v
P (tunnel)	1, 3	28.3	2.19	0.0776	12%
Q (tunnel)	6.1	36.3	2.48	0.0685	12%
R (ground effect)	0	46.7	1.23	0.0263	16%
S (ground effect0	5	83.0	1.57	0.0190	35%

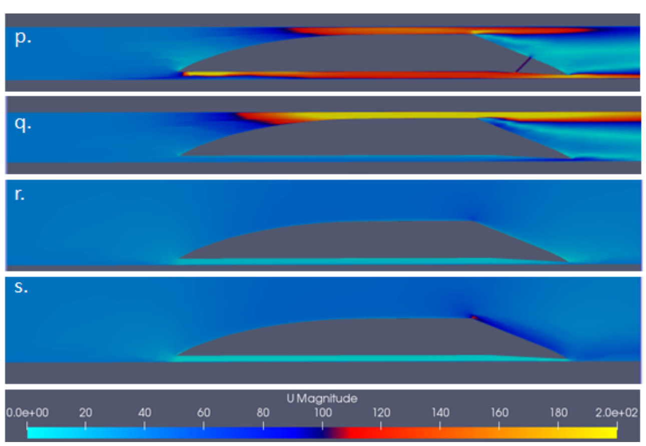


Figure 5. Velocity profiles of models p-s. Velocity is in m/s. Velocity is relative to the vehicle.

More on Laminar Flow – The results of this work are able to provide improved insight into laminar flow. An inspection of iconic laminar flow profiles, with emphasis on zero velocity at the surface boundaries of a laminar flow profiles. It is easy to come to the conclusion that the fluid is sticking to the surface. For gases, the conclusion that the gas is sticking to the surface is in error similar to the erroneous Coanda Effect.

The zero velocity condition at the gas-surface interface is a result of gas molecules "bouncing" off the solid surface at random directions. The solid surface tends to be rough at the molecular level, leading to gas molecules having relatively random velocity vectors upon reflecting off the solid surface.

In more rigorous analyses of the gas-solid interface, "slip" can occur with is conservation of part of the velocity vector in the gas-solid collision. However, in the uncommon conditions where slip occurs, the slip is relatively small compared to the random aspect of interface dynamics.

Closing Thoughts on CFD and Uncertainty – For an engineer to compete in today's environment, the engineer needs to be an expert at handling uncertainty (i.e. risk). A half-century ago, the primary engineering resources were textbooks and performance of physical prototypes. Today, Wikipedia, Google, AI, and digital prototype simulations are able to provide answers in a mere fraction of the time of textbooks and physical prototypes. Engineering productivity demands that the digital tools be used as part of engineering, and better engineers are the ones with best judgment and understanding of the accuracy of those digital tools.

The 2D pressure profiles of this paper were generated using SimFlow, which has good 2D simulation capabilities. Key results on race car and GEFT simulations have been verified using 3D CFD with OpenFoam, which is an open source software [9-12]. For 3D simulations of GEFT and the race car, fences (aka skirts) are used on the sides of the lower cavity to block lateral dissipation of pressure forces. While the 2D simulations of this paper have limited quantitative accuracy, they have accurate qualitative features towards substantiating the Three Principles without the complexity that can occur when lateral dissipation of pressure is considered.

This paper is presented as a work with three levels of rigor: 1) molecular mechanics (discussion of gas molecules and interactions and Three Principles), 2) continuum mechanic (CFD simulation results), and 3) accuracy in extrapolation (CFD results of innovations). "Scientific proof" is merely a concept and open to interpretation. Ultimately, a consistency in the science through extrapolation only presents a case on whether the science-based explanations are more likely than not.

BIOS

Adam B. Suppes received his PhD in chemical and biomolecular engineering from the University of Pennsylvania, Philadelphia, PA, USA in 2022 and his Bachelors of Science from Johns Hopkins University in chemical and biomolecular engineering. He is a researcher with HS-Drone, LLC Charlottesville, VA. His current research includes computational fluid dynamics for ground effect vehicles and planform aircraft.

Galen Suppes (Fellow, AICHE). Dr. Suppes is the founder of HS-Drone LLC, a company specializing in digital prototypes of multimodal transportation ranging from railcars to aircraft. Dr. Suppes has over 125 refereed publications cited over 8300 times and has taught chemical engineering design for over 15 years at the University of Missouri and University of Kansas. For 40 years his work has emphasized increased energy efficiency and sustainability including the lead of the 2006 awardee of the Presidential Green Chemistry Challenge. Galen Suppes received his PhD in Chemical Engineering from the Johns Hopkins University and his bachelors in Chemical Engineering from Kansas State University.

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