J. Fluid Mech. (2010), *vol.* 647, *pp.* 3–12.
doi:10.1017/S0022112010000121

Stephen H. Davis – 70, and counting

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(Received 14 August 2009; revised 21 December 2009; accepted 28 December 2009)

Celebrating the occasion of his 70th birthday, observations are offered on the life and technical contributions of Stephen H. Davis, Editor of the *Journal of Fluid Mechanics*.

1. Introduction

'Timing!' This word is not only the punch line to one of Steve Davis's favorite stories, it is a word that appropriately characterizes several aspects of his life of (so far) 70 years. Whether it is selecting the right place at the right time for his education, realizing that he had met his partner for life, recognizing the right times and places for professional change or knowing which research fields and problems would benefit most from his attention, Steve has had a talent for doing the right thing at exactly the right time.

Throughout a distinguished professional career that has spanned more than 45 years to date, Steve's research has been at the cutting edge of hydrodynamic stability, interfacial fluid mechanics and crystal growth. He has had the good fortune to be at outstanding places at times that have encouraged his substantial talents to flourish and the wisdom to make the most of these opportunities; moreover, he has the ability to get the best from those around him.

What follows is a brief account of some personal aspects of his life (coloured heavily by my personal observations while I was his student at Johns Hopkins), a discussion of a few of the important research contributions Steve and his collaborators have made and some words on the lasting nature of the impact that Steve Davis has made on the field of fluid mechanics.

2. Personal life

Stephen Howard Davis was born on September 7, 1939 in New York City, the first of a pair of sons born to Eva and Harry Davis. Steve's mother was a concert pianist and the musical 'granddaughter' of Frédéric Chopin, but decided to forego pre-concert 'butterflies' for a career teaching music. Steve's father was a dental mechanic early in Steve's life, but transitioned to cabinet making. The Davis family resided in Brooklyn until Steve was three years old and then moved to the city of Long Beach on Long Island, in part because of Steve's asthma.

Steve entered university at age 16. Despite being offered a full scholarship to Brooklyn Polytechnic, Steve preferred to attend Rensselaer Polytechnic Institute (RPI) in Troy, NY, from which he received an undergraduate degree in electrical engineering in 1960. Among his activities as an undergraduate was serving as co-captain of the RPI bowling team with future fluid mechanician Don Boyer (who, Steve likes to

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point out, always dropped the ball behind him on his approach, a trait Don denies vehemently). Steve transitioned from electrical engineering to mathematics for his graduate education, earning an MS in 1962 and a PhD in 1964 under the supervision of Lee Segel for work on the influence of free boundaries and property variations on thermal convection. While in graduate school, Steve became part of the great RPI tradition in applied mathematics, learning from not only Segel, but such giants in the field as Dick DiPrima and George Handelman. The atmosphere in the department during Steve's tenure was one in which the line between faculty and graduate students was blurred. Students and faculty interacted as colleagues; George Handelman, in particular, had an open-door policy regarding students in his home and stories of visiting students spending the night sleeping on the floor were not uncommon. Word has it that one of George's daughters, when she was six or seven years old, announced to her parents that she was going to marry Steve Davis; the daughter of Dick DiPrima was heartbroken upon learning the news years later that Steve was indeed about to marry. Steve was an avid bridge player while at RPI. Once, he was asked if he would be willing to substitute for one of the graduate students at the weekly bridge club. The student, Bob Sidman, who enlisted Steve for this task figured he should clear it with Professor Paul Slepian, who would be Steve's partner, so he telephoned the professor, asking if he would consider playing bridge with Steve Davis that evening. Slepian's response was a simple, 'Yes, no'.

Following the receipt of his PhD, Steve moved west, taking a job at the Rand Corporation, a well-known 'think tank' located in Santa Monica, California. One story he is fond of recalling is the time when he encountered a colleague staring at a messy nonlinear differential equation on the blackboard in his office. When Steve inquired as to what he was doing, the colleague replied that if he could find just 'one' solution to this equation, he would be famous. Steve looked at the board for a few seconds then said, 'How about y equals a constant?', to which the colleague shrieked, 'That's it!'

It was while working at Rand in October, 1964, that Steve met Suellen Lewis formerly of Dallas, Texas, who was working as a management trainee in personnel administration at the headquarters of Union Bank in Los Angeles. The meeting occurred at a party thrown by a mutual acquaintance. Their first formal date consisted of dinner at a French restaurant, followed by a theatre production of *The Fantasticks*. Suellen says that she and Steve never discussed marriage and dated for a year before Steve even met her parents. Following a New Year's trip to Lake Tahoe, Steve told Suellen that he had been offered a position at Imperial College in London and asked if she would go with him. Suellen protested that her parents would never stand for such a thing, their not being married, to which Steve replied that he meant he was asking her to go as his wife. Not having planned ahead, Steve had no engagement ring on hand to give Suellen, so his fraternity pin had to suffice. They were married less than two weeks later on January 15, 1966 at the Highlands Inn, a beautiful setting in Carmel, California; Rand colleague and future University of Arizona chemical engineering professor Joe Gross served as best man. Suellen has been such an integral part of Steve's life that many of his professional colleagues know her as well as they do him. They even share a September 7th birthday, although Suellen is 'much' younger than Steve. It is difficult to imagine Steve without Suellen by his side; the serendipity of a chance meeting at a party has played a pivotal role in his life.

Steve served as a Lecturer in the Department of Mathematics at Imperial, continuing his work on thermal convection and interacting with people such as Trevor Stuart. Significant effort during this period, however, was expended figuring out how to survive as a newly married couple in London on the salary paid to an Imperial College Mathematics Lecturer.

In 1968, Steve decided to return to the States, taking a position as an assistant professor in the Department of Mechanics at The Johns Hopkins University. Steve rose quickly through the ranks, advancing to an associate professor two years later, then to professor in 1975. The Mechanics department at Hopkins was truly world-class, but also rife with in-fighting. Those of us who were graduate students there during the 70's often used to joke that it was a department with ten faculty broken into ten factions. Personalities ranged from the leader of the rational mechanics group, Clifford Truesdell, to metallurgists like Bob Pond. However, the attraction to Steve was the existence of a significant group in fluid mechanics, led by Stan Corrsin and including Les Kovasznay, Bill Schwarz, Bob Long, Owen Philips and Francis Bretherton.

The epoxy that held together what George Lea, former National Science Foundation Fluid Mechanics Program Director, once referred to as the 'Johns Hopkins fluid-mechanics mafia' consisted of resin and hardener in the persons of Stan Corrsin and Steve Davis. Stan had brought to Hopkins the atmosphere he experienced as a graduate student at Caltech during the days of von Kármán and, with the arrival of Steve, that atmosphere blossomed to its fullest; Steve's experiences at RPI no doubt helped. At daily (Monday–Saturday, although Steve always skipped the weekend) 10 a.m. coffees, Steve and Stan held court over a group of faculty, graduate students and staff, all of whom addressed each other by first names, with discussions ranging from research to politics to (more often than not) topics of a humorous nature. Some of these stories cannot be related here, even if 'names were changed to protect the innocent', but a good time was always had by all. In addition to the mechanics crowd, we would be visited by Bruce Marsh, a volcanologist whose theory on the formation of island-arc volcanism included the break-up of strands of magma due to hydrodynamic instability, and Lucien Brush and Jerry Gavis of the Department of Geography and Environmental Engineering (DoGEE, always referred to as the 'doggy' department) and, of course, any visitors to the department. Graduate students would sign up for the responsibility of making the coffee each week and Stan served as the custodian of the pastries that would be brought to share on a table covered with old *Punch* magazines that was adjacent to the wind tunnel. After each session, Stan would put plastic wrap around the crumbs that were left so that they could be brought down the next day. Stan, a product of his upbringing, would never take the last piece of anything. On one occasion, he picked up a knife to cut a miniscule piece of day-old pastry in half for a final bite when he was stopped by Steve, who warned him, 'Stan, if you cut that in half, it will be accompanied by a tremendous release of energy!' He did it anyway. Occasional ping pong games would follow coffee, given that the table was next to the sinks where we rinsed out our cups. Steve proved to be a fierce competitor, one I was never able to beat.

The hours spent at coffee were magical, spawning camaraderie amongst the group that was likely unmatched at any other university at that time. Many of us who were students at Hopkins during this period and who moved on to academic careers have attempted to recreate this atmosphere at our subsequent institutions without any success whatsoever. It's as if this group of individuals – and Steve and Stan, in particular – constituted a 'primordial soup' from which the group's personality emerged spontaneously, never to be re-created in another laboratory.

Steve and Stan shared distaste for pomposity from any source. One of the jokes Steve used to like to tell at Hopkins was the story about a young boy whose mother caught him stimulating himself as young boys are wont to do. The mother told her son to stop it or he will go blind, to which the boy replied, 'How about if I only do it until I need glasses?' Bruce Marsh knew this joke well and recounts the story of seeing Steve sitting across the room at a meeting of the Hopkins Academic Council. At the podium, one of their colleagues from another department was waxing philosophical about some particularly esoteric academic issue. Bruce glanced over at Steve and saw him remove his glasses, offering them in the direction of the speaker. Bruce understood immediately the intent of the gesture.

Stan and Steve, despite their close friendship, only collaborated formally on a single piece of work, a model of maternal blood flow in the placenta, done along with Fadel Erian. They were involved in co-teaching a course on the mechanics of animal motion and interacted with bioengineering colleagues at Hopkins' medical school. One story recounts a meeting at the medical school during which one of the particularly snooty medical faculty stood up to leave, announcing that it was, 'time to go save lives'. Steve didn't let him off easily, reminding him, 'No, the "best" you can do is prolong them a bit', a remark that got a rousing ovation as the physician left the meeting room.

In 1978, the administration at Johns Hopkins decided to reinstitute a school of engineering, having received a gift to name the new school. Steve thought about staying, perhaps even as chair of one of the new departments, but was frustrated by what he viewed as a lack of serious commitment from the university administration to the new endeavor, so decided to leave Hopkins. Although the University of Arizona was attractive to Steve (and he to them) in light of his continuing problems with asthma, it was Northwestern University that won out. Steve moved there in December of 1978. The decision to leave Hopkins, and Stan in particular, was not an easy one. As Steve recounts in his and John Lumley's *Annual Review of Fluid Mechanics* article about Stan (Lumley & Davis 2003), a visit to Stan's office late one afternoon to tell him of his departure ended up in their being found by Jim Grotberg 'on the floor giggling', having consumed all the alcohol Stan had squirrelled away in various parts of the office.

Steve's initial appointment at Northwestern was in the Department of Engineering Sciences and Applied Mathematics, but he also holds appointments currently in the Departments of Mechanical Engineering and Chemical & Biological Engineering. At Northwestern, he has continued his work in interfacial fluid dynamics, much of it done in collaboration with George Bankoff, and expanded his interests in solidification, a subject area that first caught his attention at Johns Hopkins when co-advising the doctoral work of Jon Dantzig. Working with Peter Voorhees, Mike Miksis and many others, Steve has applied his knowledge of fluid mechanics and stability theory to tackle a variety of such problems.

3. Research

The curriculum vitae of Steve Davis, at the time of this writing, lists more than two hundred papers published in archival form. Many of these papers are co-authored with the 36 doctoral students he has supervised (or co-supervised) or the many post-doctoral fellows who have worked with him. A complete discussion of the scope of Steve's work is impossible in limited space (and by someone with incomplete knowledge of the numerous fields covered by his research), so I have chosen to focus on the contributions made in just a handful of these papers.

Timing is indeed a hallmark of many of Steve's contributions, in that he has a knack for choosing fundamental, tractable, timely problems that stimulate work in the field by other research groups. His mentorship of students is also well regarded, as evidenced by the many former students and post-docs who have gone on to distinguished careers both in and out of academia, some of them producing academic grandchildren and great-grandchildren who are likewise contributing to the field. Those who have been fortunate enough to have worked with Steve marvel at his grasp of the problem at hand, his ability to explain complex phenomena in simple terms and his talent for seeing the way to a solution. A side benefit of these interactions, apparent from the previous section, is that humour is never far below the surface.

Another feature of Steve's work, apart from the significance of the results, is the quality of his writing. His papers are clear and to the point, seeking to illuminate the connection between mathematics and physical explanations of results. The brief synopses below highlight but a few of his contributions.

3.1. *Fluid-mechanics research*

3.1.1. *Finite-domain effects*

An early example of a lasting piece of research by Steve is his paper on the linear stability of thermal convection bounded by lateral sidewalls (Davis 1967). Previous researchers had either posed the proper boundary conditions incompletely on these walls or idealized them as constraining allowable wavenumbers, but permitting slip. Steve's analysis properly incorporated the lateral walls and yielded results in agreement with experiments that showed that, in rectangular containers, rolls with axes parallel to the short side of the container are preferred. He also demonstrated that rolls of square cross-section often observed in experiments are the case only when the depth is the smallest dimension in the problem.

The influence of a finite boundary on the stability properties of a basic state is an area that has been explored extensively, particularly in the years since Steve's work, not only in thermal convection, but in Taylor–Couette flows and problems of pattern selection, in general. Steve's 1967 paper continues to be cited regularly.

3.1.2. *Contact-line motion*

Steve's interest in interfacial phenomena can be traced to his dissertation work on the influence of deformation on stability properties of thermal convection. In the 1970's, he turned his attention to the complex motion of the multi-phase 'contact' line separating fluid–fluid–solid interfaces. In work with Elizabeth Dussan V. (Dussan V. & Davis 1974), a set of simple experiments was devised showing that fluid material points move either toward a contact line then reside on the interface between displacing fluid and solid or from the contact line to the fluid–fluid interface between displacing and displaced fluids; i.e. that there is a 'rolling' motion at play. Thus, a fluid material point in contact for a period of time with a solid surface need not remain on that surface, rendering the no-slip condition compatible kinematically with a moving contact line. It was further proved that the velocity field is multi-valued at a contact line, giving rise to unbounded forces exerted on solids by fluids in its vicinity. Steve and Liz show that anything that eliminates the multi-valued velocity at the contact line, such as a slip coefficient, remedies this problem, while cautioning that employed slip models must yield results in reasonable agreement with measurable physical quantities.

This paper was, and remains, a fundamental contribution to modelling of contact-line behaviour in interfacial flows. According to Web of Science, it has been cited at least 363 times and continues to receive regular mention thirty-five years following its publication.

3.1.3. *Instability of interfacial flows with application to materials processing*

Another problem of interfacial fluid mechanics that also overlaps with Steve's interest in solidification is the problem of thermocapillary convection driven by temperature-induced variations of interfacial tension. This problem received a great deal of attention and research support for a couple of decades due to the incidence of striations in material properties of semiconductor material grown using the float-zone crystal-growth technique. This method is a containerless one for producing, say, single-crystal silicon in which the molten material within a ring heater is held in place by surface-tension forces alone. It was observed during measurements that convective motion within the melt was oscillatory, which, when coupled with solidification, resulted in the freezing of dopants into the segregated bands referred to as striations. Given the strong surface-temperature variations present in the process, thermocapillary convection was undoubtedly present. With Asok Sen (Sen & Davis 1982), Steve examined possible thermocapillary-convection basic states in two-dimensional layers. However, it was work with Marc K. Smith (Smith & Davis 1983) on the stability of these basic states that shed new light on the issue of oscillatory convection and striations. Steve and Marc discovered a new type of instability they termed a hydrothermal wave that propagates with a frequency and in a direction relative to the basic-state free-surface motion that depends upon the liquid's Prandtl number. This permitted a connection to be made between model experiments, performed with transparent, moderate-Prandtl-number liquids and crystal-growth applications in molten silicon.

One of my students and I (Riley & Neitzel 1998) were fortunate to have been the first to experimentally confirm, quantitatively as well as qualitatively, the appearance of this instability in very thin two-dimensional layers. We also found there to be an influence of buoyancy on the stability limits. There is continuing interest in this problem and what has come to be known as the 'Smith & Davis instability', as evidenced by the fact that another paper in this volume by Chan & Chen (2009) addresses theoretically our issue of the influence of gravity on the instability.

3.2. *Materials-science research*

Being a non-expert in the field of materials science, and solidification in particular, I feel incompetent to select and discuss properly Steve's contributions in these areas. Therefore, I have asked Steve's colleagues Peter Voorhees of Northwestern University and Geoffrey McFadden of the National Institute of Standards and Technology to provide me with a few examples of such work, requesting in particular, that they identify work on which Steve has collaborated with a student or post-doc and some which have a relationship to fluid mechanics. An additional remark noteworthy to this discussion comes from Steve's friend and collaborator, Grae Worster, who stated to me,

> *I think that one of Steve's most lasting contributions to the subject is superficially trivial but is the reason that his work has had so much impact. It was simply to present stability results in terms of the experimentally controllable variables: the concentration of impurity in the melt and the solidification rate. Previous stability analyses had always been presented in terms of the non-dimensional Morphological number. It was Steve's graphs that showed most clearly that the phase boundary became unstable once the solidification rate became too large (which was what most people focused on), but then became stable again at very high solidification rates. The nonlinear morphological evolution of phase boundaries at such high modification rates was a major focus of Steve's research while I was his colleague at Northwestern University.*

Jeff McFadden comments further,

Many of Steve's significant contributions in materials science consist of applying powerful approximation techniques that have been developed by Steve and his co-workers to describe the nonlinear evolution of hydrodynamic instabilities to problems involving interfacial instabilities that occur during phase transitions. Previous theoretical work in the field was often based on linear analyses that could be obtained analytically in special cases, followed by large-scale numerical calculations to extend the linear theory. Steve is a master at finding useful analytical approximations based on the careful identification of appropriate regions of parameter space in which nonlinear solutions can be obtained without resorting to purely numerical approaches. In this way he has been able to provide deep insights into the physical mechanisms at play, which are frequently obscured in computational studies. In the process he often extends linear theories into more useful nonlinear descriptions of complex experimental instances of pattern formation. The hallmark of Steve's work in this area is the emphasis on physical explanations of the predicted phenomena; the role of the mathematical techniques that are employed along the way, while powerful and elegant, are secondary to the valuable insight provided by his work.

What follows are a few paragraphs that Peter and Jeff have provided graciously, edited slightly to make the style consistent.

3.2.1. *Thin film growth*

With doctoral student Brian Spencer, Steve and Peter Voorhees examined the linear morphological stability of epitaxially deposited thin films (Spencer, Vorhees & Davis 1991, 1993); these papers have been cited 275 and 188 times, respectively. The instability is driven by elastic stress in this case. The paper outlined the conditions under which quantum dots can form on surfaces, such as silicon.

Steve has also demonstrated his ability to conduct meaningful research with undergraduate students, as evidenced by his paper with McCallum *et al.* (1996), in which Steve, Matt McCallum and others examined the morphological stability of a thin line of solid film that was deposited on a substrate. The objective of their work was to examine the effects the presence of a contact line have on the classical Rayleigh instability of a rod. The film evolves by surface diffusion in this case.

3.2.2. *Solidification*

Merchant & Davis (1990) identified a new oscillatory instability that was postulated to be the source of the banded structures that people had observed during rapid laser melting of surfaces. This result is an example of Steve's outstanding ability in modelling, in this case the addition of solid–liquid interface properties that depended on interface velocity.

Rapid solidification leads to many new and interesting phenomena (such as the banding mentioned above). Steve realized that high solidification speeds can stabilize a planar interface. This allowed Brattkus & Davis (1988*a*) to determine strongly nonlinear non-planar interface shapes in a new parameter regime.

One of Steve's post-doctoral fellows at Northwestern was Sasha Golovin. An early example of their collaboration is Golovin, Davis & Nepomnyashchy (1998), which is a beautiful paper illustrating how modelling and the methods of applied mathematics can significantly contribute to understanding of physical phenomena. In this case they accounted for the energy of corners that connect facets. The addition of this corner energy regularizes the evolution equations and they were thus able to make important predictions on the evolution of the interface shapes. A result of Sasha's interactions with Steve was that it was clear that Sasha was an extraordinarily talented person.

He was thus eventually hired as a faculty member in the Department of Engineering Sciences and Applied Mathematics at Northwestern, where he, Steve and others continued their work together. Sadly, Sasha recently passed away, a victim of cancer.

3.2.3. *Solidification and flow*

Work on the interaction of flows and morphological stability during solidification is a natural area for Steve. The paper Brattkus & Davis (1988*b*), with doctoral student Kirk Brattkus, is but one example of an important paper that examined the influence of flow on morphological stability during solidification. Another paper of note is that with his student Gerry Young (Young & Davis 1986) investigating the role of buoyancy in directional solidification.

A particularly beautiful example that combines his interests in fluid mechanics and materials science is work with Müller and Dietsche (Davis, Müller & Dietsche 1984). Here, in a variation of the classical Bénard problem, a horizontal fluid layer is heated from below and cooled from above, the cooling being strong enough that the liquid solidifies at the upper boundary. The stability of the conducting liquid is therefore affected by the presence of a phase boundary, which alters the thermal conditions at the top surface of the liquid. The experiments described in the paper show a transition in the ensuing secondary convection pattern from rolls to well-defined hexagons as the depth of the solid layer varies, and Steve and his co-workers are able to provide a nonlinear theory that describes the transition accurately and explains the underlying instability mechanism in terms of the heat transfer at the solid–liquid interface.

Steve has produced a monograph on solidification entitled 'Theory of Solidification' (Davis 2001). Those of us who have studied hydrodynamic stability under his tutelage are still hoping that an updated version of his collection of handwritten and typewritten notes on that subject may one day find its way into book form.

3.3. *Summary*

The brief summaries of research contributions given above do not begin to do justice to the breadth and depth of the work of Steve Davis, nor do they yield a complete sense of the importance of this work and the esteem in which it is held by his colleagues in the research community. A hint of that may be provided by the fact that Steve is a recipient of the Fluid Dynamics Prize of the American Physical Society (of which he is also a Fellow) as well as an elected member of the National Academy of Sciences, the National Academy of Engineering and the American Academy of Arts and Sciences.

4. Closing

On the occasion of Steve's 70th birthday, it is fitting that the other members of the editorial board of the premier journal in our field, unbeknownst to him, have chosen to honour Steve with this special volume of *JFM*. Although aspects of his personal life and contributions through research have been noted above, absent from this discussion has been the mention of his other contributions to the field through his service as editor of *JFM, Annual Review of Fluid Mechanics, Proceedings of the Royal Society of London* and various monograph series and his advocacy for mathematics, science and engineering through service on various governmental advisory groups and national committees. For all these things, the community of his friends and colleagues around the world wishes Steve a happy 70th birthday, with many more to follow.

Finally, back to the issue of timing and to the story Steve enjoys telling. *The Tonight Show* has been a staple of late-night American television since 1954; for thirty years, from 1962–92, the show was hosted by the late Johnny Carson. One of Johnny's frequent guests was Buddy Hackett, a short, portly comedian with an unusual, nasal-toned voice. One night, as a guest on the show, Buddy was seated on the chair next to Johnny when a new guest was introduced, a 'starlet' whose name Steve doesn't remember, probably for the best. Guests were often, at this time, invited to do a bit of stand-up comedy before taking the seat next to Johnny's desk and this individual's attempts at telling jokes were particularly pathetic! Buddy was beside himself over the quality (or lack thereof) of this young woman's attempts at humour, so decided to educate her as she took his chair and he moved to the adjacent sofa. The lecture that ensued went something like the following:

Hackett (to Starlet): I want you to repeat, after me, the following sentence: What is the most important thing in comedy?
Starlet (responding, as instructed): What is the most import . . .
Hackett (interrupting forcefully): TIMING!!!

Timing, indeed. Steve not only has been at the right place at the right time geographically – from RPI to California, Hopkins to Northwestern – but he has chosen to enter research areas at defining moments, producing fundamental, enlightening work that has enabled others to also advance the respective areas. We all eagerly await the next insightful contribution from one of the true leaders of our field.

I am indebted to Peter Voorhees and Jeff McFadden for providing synopses of a few of Steve's many contributions in materials science and solidification. I am grateful to the late Bob Pond, then chair of the Department of Mechanics and Materials Science at Johns Hopkins, for escorting a young guy to the coffee room the morning that I visited to inquire about graduate school to meet this almost-as-young faculty member with whom he felt I might hit it off. But mostly, I am forever thankful for the opportunity I had to work with Steve Davis and for his mentorship, good humor and friendship over the thirty-five years since that first meeting at coffee.

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