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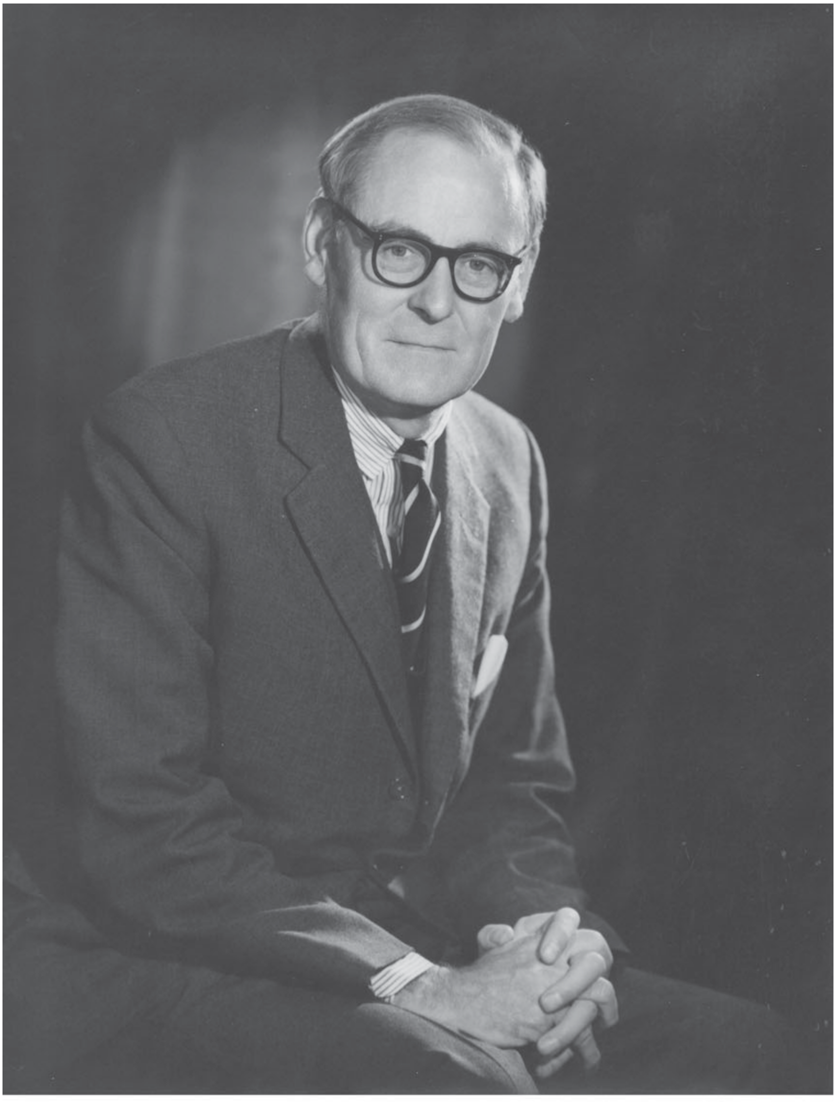

W. R. Hawthorne

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Elected FRS 1955

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William Rede Hawthorne was a pioneer in gas turbine aerodynamics and thermodynamics, a sought-after technology advisor to industry and government, and a generous and enthusiastic teacher who encouraged students to excel. His outstanding contributions included resolution of combustion problems that limited the operation of the original Whittle jet engine, early in-depth descriptions of compressible channel flow that still inform engineers today, innovative and wide-ranging analyses of secondary flows in turbomachinery that defined the field, and creation of some of the first notes on gas turbine cycle analysis. A theme in the many areas of engineering in which he had impact was the satisfaction from the growth of understanding that can accompany making things work—in his words, 'machines produce ideas just as surely as ideas produce machines'. A Cambridge graduate, he was a professor at MIT when, in 1951, he was recruited to a newly established chair at Cambridge, where he later had leadership roles as head of the engineering department (1968–73) and Master of Churchill College (1968–83). He retained strong ties to MIT, however, and fostered lasting collaborations between the two universities. Among his numerous awards and honours were the US Medal of Freedom (1947), a Royal Society Medal (1982) and a knighthood (1970) for 'services to thermodynamics', a citation that pleased him greatly.

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Family background, early life, education at Cambridge, initial career (1913–1935)

Sir William Hawthorne, a mechanical and aeronautical engineer who was a pioneer in the aerodynamics and thermodynamics of gas turbine engines, was born on 22 May 1913 at 11 The Grove, Longbenton, Newcastle upon Tyne. He was the first of three sons of William Hawthorne (1878–1957), a civil and electrical engineer, and his wife, Elizabeth Curle, née Greenfield (1882–1952). His father was born in Northern Ireland and his mother, one of the first women biology graduates of the University of Glasgow, in Edinburgh. They had come to Newcastle in order for his father to join the leading engineering firm of Merz and McLellan, who had made their reputation in Newcastle in the new field of electrical power generation and distribution.

Hawthorne was educated at the Dragon School and at Westminster School, where he rowed and also acted. In 1931 he won an exhibition to Trinity College, Cambridge, where he read mathematics for a year and then mechanical sciences for two years. By then his family had moved to London and then to Esher, where Merz and McLellan established an office. Hawthorne took a particular (and continued) interest in thermodynamics, winning the Ricardo Prize in that subject. He received firsts in mathematics and engineering and shared the Rex Moir Prize awarded to the best student in the Mechanical Sciences Tripos. His extra-curricular activities included rowing for Trinity and an active participation in the Pentacle Club (magicians), appearing in their London revue with his sleight of hand show. He maintained a life-long love of conjuring, as described later. After leaving Cambridge, he became a graduate apprentice at the boiler-making firm of Babcock & Wilcox Ltd, near Renfrew.

ScD thesis at MIT, Babcock & Wilcox, marriage to Barbara Runkle (1936–1939)

Hawthorne wished to undertake a research degree, and his exceptional academic record led to his receiving a Commonwealth Fund fellowship in 1935 for graduate study in the Department of Chemical Engineering at the Massachusetts Institute of Technology (MIT), in ‘the other’ Cambridge. There he completed an ScD on the aerodynamics of combustion, working with Professor H. C. Hottel.

It was Hottel who introduced Hawthorne to the fascination of engineering science research and who showed him the power of analysis in engineering problems (Anon 1961). His thesis topic was ‘The mixing of gas and air in flames’. His research addressed the mixing of burning jets of combustible gas to determine the influence of turbulence on flame length, showing that the rate of mixing, i.e. the rate at which oxygen mixes with fuel, controls the length of the flame (3)*. The findings from his ScD research would enable him to help Sir Frank Whittle (FRS 1947) several years later in the development of the first jet engines in the United Kingdom.

In 1937 Hawthorne rejoined Babcock & Wilcox as a development engineer, where he worked until the outbreak of the Second World War addressing a range of boiler and furnace design issues. While in America he had met Barbara Runkle, a graduate of Radcliffe College

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* Numbers in this form refer to the bibliography at the end of the text.

and a granddaughter of MIT’s second president, John D. Runkle. He returned to America in April 1939 to marry Barbara, at the Unitarian church in Harvard Square. After the outbreak of war, Barbara went back to the USA, where their son, Alexander, was born in 1940.

RAE, Secondment to the Whittle jet engine project (1940–1941)

In 1940 Hawthorne was directed into a reserved occupation as a scientific officer in the Ministry of Aircraft Production, but after a short time at the Aircraft Testing Establishment at Boscombe Down, he moved to the Royal Aircraft Establishment (RAE) at Farnborough. There he joined the Engine Research Group to lead a team on combustion chamber development. At that time, in great secrecy and with Winston Churchill’s personal support, Frank Whittle’s work on the development of his newly invented jet aero-engine prototype was being conducted at the British Thomson–Houston works at Lutterworth, Leicestershire. Progress was stalled, however, by the occurrence of combustion problems. These problems were a major issue because the engines could not be made to run for the required length of time. In Hawthorne’s words, ‘The heat release rate (watts/cubic meter of combustion chamber volume) was at least an order of magnitude greater than that in industrial furnaces, even allowing for the increased density of the gases in the chamber’ (8).

Shell had developed a swirl-type atomizer that gave an appropriate spray over the desired fuel flow range, with a combustion chamber similar to a domestic oil burner (7). Associated with the high heat release needed for engine operation, however, were restrictions on the engine run times to 45 minutes or less. In Hawthorne’s words, again: ‘Each engine run had to be terminated after red and orange patches on the combustion chamber walls threatened to burn holes in them, and [fuel] vaporizer tubes would be found blocked with carbon and burned.’

Hawthorne’s doctoral thesis research bore directly on the Whittle jet engine’s difficulties, and he was ‘loaned’ (as he would say) to Power Jets, the company formed to develop the engine. His knowledge of fluid dynamics proved crucial to developing a design philosophy for stable combustion. A principal result in his thesis was that, over an enormous range, the length of a turbulent diffusion flame was dependent on the geometry and not the heat release rate, implying that aerodynamic mixing dominated the flame length. He reasoned that if flame stability were achieved, the domestic oil burner configuration could operate at the high heat transfer rates desired.

Under Hawthorne’s direction, the prototype jet engine’s combustion chambers were altered to improve the dispersion of droplets of fuel within their air streams, enabling the prototype engine’s development to continue. Swirl vanes were used to create a recirculation zone, and thus to stabilize the flow, in other words to provide a *flame holder* with low enough velocities so the flame sat stably at a given location instead of being blown downstream. The first successful flight of a Gloster E28/39 jet aircraft, with the improved combustion chamber, took place on 15 May 1941.

Initially, holes and pipes were used to create high levels of mixing, but other devices were used, including lobed mixer nozzles, which provide streamwise vortices that stir the flow to enhance mixing. These nozzles are found today (more than 70 years after their invention) in jet engines and other devices, such as ejectors and jet pumps that rely on mixing for their operation. Hawthorne recounted that a major lesson furnished by this work was that ‘as much care was required in determining and assuring the aerodynamic features of the combustion chamber and its fuel injectors as in the design of a blade for a compressor' (8).

HEAD OF TURBINE DIVISION, RAE, AND MINISTRY OF AVIATION (1941–1946)

Division mission and organization

In August 1941, Hawthorne returned from his year's secondment to Power Jets to become head of the newly formed Turbine Division at the RAE, which reported to Hayne Constant (FRS 1948), the head of the engines department. The Division set out to become the government's 'back room' for the new jet engine. Objectives and work carried out included measuring physical processes in the propulsion system, experimental research, performance calculations, project studies, designs and design information (6). Constant persuaded the Ministry that all projects for gas turbine engines should be vetted through the Division, which further enhanced its body of knowledge. The Division produced more than 250 reports or technical notes in the three years between 1941 and 1944, provided the aerodynamic design for the turbine of the de Havilland H1 (Goblin) and the layout of its combustion chambers and provided instrumentation and flight facilities.

The Turbine Division was divided into five sections: Aerodynamics, Design, Mechanical Test, Combustion, and Performance. We mention these by name because this was an initial definition of an organization to develop jet engines; the thoughts about identification of the different sections, as well as about methodology for selection of problems to be addressed, set a pattern that can still be seen at jet engine manufacturers.

Much of the work done by the Division was groundbreaking. Seen from a 70-year perspective, this was perhaps not driven primarily from research interests, but rather reflected the lack of information on gas turbine technology available at that time; the participants had to develop the fundamentals for themselves. For example, it was recognized that an increase in pressure ratio would lead to an improvement in fuel economy. There was, however, concern about achieving these higher-pressure ratios using a single spool (a single compressor and turbine) rather than a two-spool configuration. The Performance section therefore analysed both engines at design and at part speed conditions where stall problems were seen as most serious. Hawthorne later commented that, as far as he was aware, these were the first estimates ever made for the part-load performance of a gas turbine engine (6). Another retrospective comment was that the RAE team led the world at this time, both in its understanding of jet engines and in its appreciation of what was *not* understood (Anon 1961), a theme to be expanded below.

Hawthorne's view of the Turbine Division was that its primary role was to create technology that was grounded in fundamental principles and, equally important, of help to designers and users in industry. He felt strongly that 'as soon as a government establishment goes too far into the new design or invention business it tends to lose its ability to help others and its credibility as an advisor'. This might be stated differently today, perhaps including also the range of technology readiness levels (TRLs) on which an organization focused, but the recognition of crucial differences in the roles of government and industry, and hence of the expertise needed for the former, is still an important aspect of gas turbine engine development.

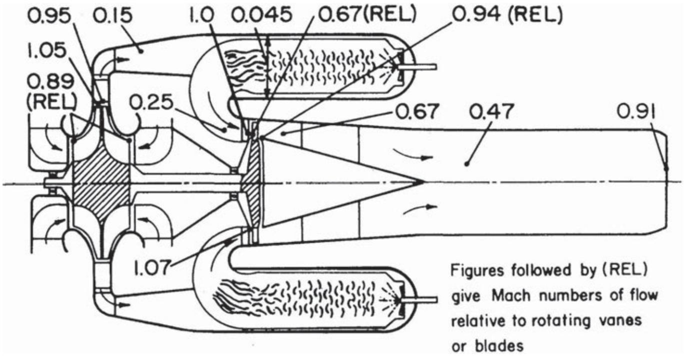


Figure 1. Typical Whittle-type turbojet engine showing values of Mach number at various points at the design engine rpm, for sea level test conditions. Reproduced from (4) with permission.

Aerodynamic issues addressed by the Turbine Division

We describe several aerodynamic issues addressed by the Turbine Division because they link with Hawthorne’s seminal work on gas turbine aerodynamics and illustrate the important steps taken in sorting out these complex flow phenomena. The first concerns compressible flow behaviour at high subsonic Mach number (Mach number is the ratio of fluid velocity to the local speed of sound). In the E28/39 aircraft, the exhaust pipe passed through the fuselage to the propelling nozzle at the aircraft tail. The turbine nozzle, which fed the pipe, had been designed for a Mach number of 0.8 at the upstream end of the pipe. When tested, it was found that as the engine speed increased the turbine inlet temperature increased much more rapidly than expected, so the rotational speed was limited to below the design value. Without the exhaust pipe the full thrust could be obtained, but the thrust was reduced to an inadequate level when the pipe was installed.

The cause of this was discovered to be *flow choking*, as a result of wall friction. Choking in a compressible flow has a specific meaning with relation to the maximum possible mass flow per unit area, which occurs at Mach number equal to one. In the situation described, there was high sensitivity of choking to wall friction because the inlet Mach number was close to unity, the choking limit, and a length of only four pipe diameters led to choking. The pipe was longer than this, so the engine was unable to pass the amount of flow for which it had been designed, creating the higher pressure and temperature at the turbine exit. The engine exhaust ducts were thus redesigned with larger cross-section and thus lower Mach numbers. Figure 1 shows a schematic of a Whittle-type turbojet engine with the values of local Mach number indicated; the design Mach numbers in the exhaust duct were decreased from 0.67 to 0.47. The influence of friction on mass flow was a striking feature of compressible flow compared with incompressible flow, as Hawthorne was later to further illustrate.

A second aspect concerns the flow through turbomachine blading in the regions near the hub and the casing, in which the flow is strongly three-dimensional. Viewing the flow around the blades in these *endwall regions* as two-dimensional, as can often be done away from the endwalls, is thus not a useful approximation. It was also known early on that the flow in the endwall regions is retarded by wall friction, compared to the flow far from the walls, with the result that the axial velocity outside the endwall regions is higher than the average along the blade span, and the angle of incidence on the blading thus less than that based on average quantities. Endwall flow features were another area Hawthorne would illuminate in great depth.

It is no coincidence that both these areas came from dealing with ‘real world’ issues of jet engine flow. A theme that threads through Hawthorne’s career is that ‘The conception and development of a machine leads to more than merely the production of a device’ (4). In this he refers to the satisfaction from the growth of understanding that can accompany making things work, given earlier in the summary. A more specific rendering of this idea, combining two of his great interests, thermodynamics and power-producing machinery, was his adage ‘Thermodynamics owes more to the steam engine than the steam engine owes to thermodynamics’. The interdependence of device and understanding was an important part of his approach and philosophy concerning problem solving in engineering.

In May of 1944 the Turbine Division was extracted from the RAE to join with the existing Power Jets Ltd to form a nationalized company, Power Jets (R&D) Ltd, a decision that was not welcomed by Hawthorne or Constant, or by Farren, the director of RAE. (The new company was reconstituted as a division of the Ministry of Supply to form the National Gas Turbine Establishment in 1946.) Hawthorne subsequently rejoined the Ministry of Aircraft Production and, later in 1944, was sent to Washington to brief the Americans on gas turbine developments in Britain. He then became deputy director of engine research in Britain’s Ministry of Supply, working for two years in Whitehall. For his wartime work he was awarded the US Medal of Freedom in 1947.

Further MIT years (1946–1951)

In 1946, Hawthorne returned to MIT as an associate professor of mechanical engineering, promoted soon after to George Westinghouse professor of mechanical engineering. His two daughters, Joanna and Elizabeth, were born in 1946 and 1948. His years at MIT were extremely productive and he produced notes and seminal papers that had a major effect on aerodynamics and thermodynamics for gas turbine propulsion and power.

Gas turbine lecture notes

The first of these were notes on gas turbine cycle thermodynamics that Hawthorne created for his classes. The quality of the notes is described by Sir John Horlock (FRS 1976) as ‘a beautiful set of notes on cycles’ that ‘remain the best starting point for the subject’. Horlock used them as an assistant professor at MIT in the mid 1950s; in the preface to his book, *Advanced gas turbine cycles* (Horlock 2003), he refers to the way in which the notes show the power of temperature–entropy diagrams in cycle analysis and acknowledges both the path-breaking nature of the notes and Hawthorne’s abilities as a ‘great engineering teacher’.

One-dimensional compressible channel flow

A contribution in a different area was a landmark paper Hawthorne co-authored with A. H. Shapiro, his faculty colleague (and, later, institute professor) at MIT (1). The paper gave a unified treatment of compressible flow phenomena, particularly as applied to the new and exciting area of jet propulsion. The central idea is that, in a compressible flow, the fluid mechanics and the thermodynamics are *coupled* in an important and interesting way and there are many such flows that can be usefully treated in a one-dimensional manner.

More specifically, the coupling means that compressible fluid motions exhibit features not present in an incompressible flow: (i) *flow choking*, as mentioned above; (ii) *supersonic flow* (flow with regions that downstream pressure perturbations cannot affect); (iii) *shock waves* (sharp transitions from supersonic to subsonic flow); and (iv) *effects of entropy changes on velocity and pressure fields*. All these features can be well illustrated using the compressible channel flow approach.

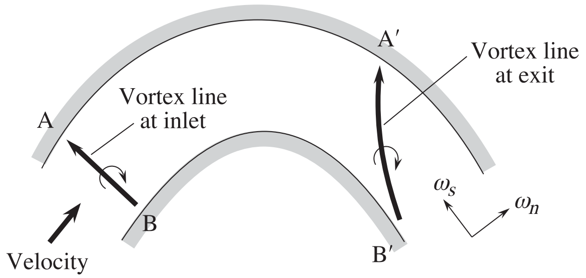
The 1947 paper was written to provide both an enabling *quantitative* treatment as well as to give insight into the *qualitative* flow features. For the former, at that time, the only way to obtain numbers for many problems was through numerical integration of one-dimensional equations. For the latter, the flow features can be seen directly from the *influence coefficients*. These are the partial derivatives of the dependent quantities: stagnation and static pressure; temperature; density; and velocity and Mach number. With respect to the independent quantities, these are the variables over which the designer may have control, such as: area variation; heat addition or extraction; friction; and mass injection. Influence coefficients allow, almost by inspection, the extraction of differences between subsonic and supersonic flow and trends with addition of mass, momentum and energy as a function of Mach number. (A feature remarked upon by Hawthorne for its pedagogic value was that there is a Mach number range—between approximately 0.85 and 1.0—over which the static temperature decreases when heat is added to a flow.) Many computational procedures exist today that can supply quantitative information, but the role of one-dimensional channel flow in giving clear insight is still very much with us as part of this legacy.

Secondary flow

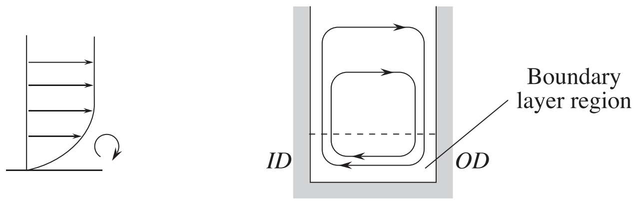
Another of Hawthorne's outstanding contributions concerns the three-dimensional fluid motions that occur when a flow with *vorticity* (non-zero local angular velocity of fluid particles) is turned, for example by obstacles or in a blade passage. A relevant situation is the flow in a boundary layer, a layer of flow near a surface that has been retarded by viscous forces, on the floor of a bent channel, as in Figure 2. Upstream of the bend the streamlines are straight, with the velocity uniform and parallel to the sidewalls. The velocity variation perpendicular to the channel floor, i.e. to the page, can be usefully characterized in terms of vorticity, and the field of vorticity vectors can be described in terms of vortex lines—lines that thread through the fluid and are tangent to the local vorticity. The utility of such a description is two-fold: the first is that if the vorticity is known, one can calculate *what* the velocity is; the second is that for a number of engineering situations vortex lines can be regarded as 'locked' to fluid particles, and tracking the evolution of vortex lines, even in an approximate manner, gives considerable insight into *why* the velocity field behaves the way it does.

These points are illustrated in Figure 2. At inlet to the bend there is a boundary layer on the floor of the passage, with uniform flow outside of this boundary layer. At inlet the vortex lines are located near the channel floor and normal to the inlet velocity, as indicated by the arrow AB. The sense of the rotation is also indicated. We can approximate this situation as a distribution of vortex lines that are convected by a non-vortical background, or 'primary' flow, and whose evolution leads to a 'secondary' motion normal to the primary flow streamlines.

As the flow proceeds round the bend, the fluid near the inner wall has a lower static pressure because of the curved path, and therefore a higher velocity, than that near the outer wall. Fluid particles on the outside wall also have farther to travel. The net result is that the line of particles, AB, initially normal to the mean flow, is oriented as A′B′ at the passage exit.



Top View of Passage



Inlet Streamwise Velocity

Secondary Streamlines at Passage Exit

Figure 2. Generation of streamwise vorticity and secondary flow from non-uniform convection of vortex lines through a bend.

Because vortex lines and fluid lines behave the same way, the vortex lines at exit are also tipped into the streamwise direction, creating a streamwise vorticity component at exit and a *secondary circulation*, as indicated in the channel cross-section at the bottom of the figure, with an inward motion of fluid in the boundary layer. This three-dimensional motion, which transports momentum and energy across a passage, is inherent in turbomachinery and other engineering flows and its effect on fluid device performance was a major Hawthorne theme.

Hawthorne's initial paper on secondary flow appeared in the *Proceedings of the Royal Society* (2), communicated by Professor Theodore von Karman from Caltech, a Foreign Member and a pre-eminent aerodynamicist of the first half of the last century. That paper, and the subsequent papers on the topic, demonstrate Hawthorne's great ability to see where the root of an engineering problem lay and to visualize its solution, often in elegantly simple mathematical terms. These skills were used with much success to unravel the intricacies of three-dimensional vortex kinematics. In this he was undoubtedly aided by his extraordinary ability to write original vector analysis of a particularly complex fluid flow as if he were writing a letter (Greitzer & Horlock 2013). The 1951 paper, for example, starts with the equations of motion written in compact vector form (2). The vector manipulations that follow turn these compact expressions into what seem longer and more complex statements. Just before the reader gives up all hope, however, several trenchant substitutions compress the long statements into greatly shortened forms that connect the growth of the three-dimensional motion to readily-grasped physical quantities such as acceleration, leaving much the same admiring gasps as did his feats of magic for the Pentacle Club.

CAMBRIDGE YEARS: HOPKINSON AND ICI PROFESSOR OF APPLIED THERMODYNAMICS (1951–1980), HEAD OF UNIVERSITY ENGINEERING DEPARTMENT (1968–1973)

In the early 1950s, Sir John Baker (FRS 1956; later Lord Baker), head of the University of Cambridge Department of Engineering, was expanding the department. New laboratories were being built at Trumpington Street, and engineering was becoming the university's largest department. Baker had raised funds for a new chair of thermodynamics, and he travelled to the USA to help persuade Hawthorne to return. The result of this mission was that Hawthorne was appointed as the first Hopkinson and ICI Professor of Applied Thermodynamics in 1951 and to a fellowship at Trinity College.

At Cambridge, Hawthorne made a great impact, with the help of two brilliant young staff, John Horlock and Arthur Shercliff, both of whom later became professors at Cambridge and Fellows of the Royal Society. Working together, they developed a new undergraduate teaching course in thermodynamics based on ideas Hawthorne had brought from Professor Keenan at MIT. A new syllabus was introduced with smaller than usual classes, bringing a rigorous and disciplined approach to what had been a woolly subject in engineering courses. This intellectual rigor proved a wonderful training for analysing problems, and developments of the approach became widely taught in engineering departments around the country (Newland 2013).

When Hawthorne was elected to his Cambridge chair, university professors did not supervise undergraduate students. He ignored this tradition, and regularly supervised the progress of final-year students. For students, at least initially, this could be an unnerving experience because they often took part in discussions on important current engineering issues, which Hawthorne led with characteristic wit and sparkle.

For a number of students in the late 1950s these discussions centred on *dracones*, known irreverently as Hawthorne's NOBs (nylon oil barges). These were huge (some up to 90 m long) nylon sausages, that could be towed behind a ship to transport oil and other liquids. Hawthorne developed the concept in response to the Suez crisis of 1956, when British oil supplies through the Suez Canal were disrupted and tankers had to sail around the Cape of Good Hope. Work on dracones dominated research in Hawthorne's laboratory for several years. After initial small scale (roughly 3 m long vessels) experiments in the National Physical Laboratory's (NPL's) ship tank at Teddington, a team of graduate students was mobilized to carry out towing tests on the River Great Ouse at Ely, where *Draconella*, a 0.75 m diameter, 20 m long vessel with a capacity of 10 tons, was launched and tested in April 1957.

The first flexible barge initially snaked uncontrollably from side to side and there were difficulties in obtaining waterproof fabric strong enough to make a viable barge, but these problems were addressed. The Suez crisis passed before dracones could be used for their original purpose, long distance transport of oil, but they were used in the Falklands, before, during and after the 1982 conflict, for oil deliveries in other remote locations and as containers for waste oil recovered from oil spillages at sea.

Hawthorne's aircraft engine turbomachinery research also blossomed. He extended his descriptions of secondary flow to different types of geometries such as flow around struts, fluids of non-uniform density, and flow in rotating blade passages. With non-uniform density there is the capability for internal generation of vorticity due to the interaction of pressure and density fields, so there can be competing effects of the distortion of existing vorticity and the creation of new vorticity. In rotating blade rows there is, for an observer in a rotating system, a non-conservative body force, the Coriolis force, which can give rise to vorticity, again bringing in new physical features. These analyses and complementary experiments led to important insights into non-uniform flows in turbomachines and enhanced effectiveness of gas flow within these devices, helping improve the efficiency of jet engines.

Hawthorne also addressed the topic of axisymmetric flow in turbomachine annuli. This had been treated by the so-called radial equilibrium approximation, in which the streamlines were taken to be cylindrical surfaces, the radial component of velocity was neglected, the inner and outer radii of the annulus containing the blades viewed as constant and the radial pressure gradient thus balanced by the centripetal acceleration. This approximation was appropriate when radial variations of density and blade circulation were not large. For conditions in which this restriction did not hold, Hawthorne and Horlock, and others, developed an enhanced approximation in which the radial velocity could be included. This analysis made use of the concept of an *actuator disk*, a surface in the flow across which there could be discontinuities in velocity, pressure and entropy. Hawthorne and Horlock did not invent the concept, but they made considerable use of it for annular flows with radial variations of momentum and energy and their joint paper (5) received the James Clayton Prize of the Institution of Mechanical Engineers. The analyses they developed have been superseded by computational procedures, but a number of useful ideas concerning flow features (rate of decay of radial velocities upstream and downstream, for example) that emerged from the work are still useful.

SRC Turbomachinery Laboratory, 1973

In 1968, Hawthorne succeeded Baker as head of the engineering department. A major achievement during his tenure concerned the creation of a new laboratory focused on turbomachinery. With the work of John Horlock especially, but also other colleagues, the growth of the department’s turbine engine research led to a need for more laboratory space.

Horlock had experience as a member of the Mechanical Engineering Committee of the Science Research Council (SRC), and he and Hawthorne collaborated in a joint application to the SRC to set up a new laboratory dedicated to turbomachinery. The result was the SRC Turbomachinery Laboratory, opened by Sir Frank Whittle in 1973 (Denton & Gostelow 2016). Figure 3 shows Hawthorne, Horlock (the first director) and Whittle at this occasion, along with other jet engine pioneers. The laboratory was the first engineering building on a large, open site in west Cambridge, some way from the rest of the engineering department. The name was changed to the Whittle Laboratory in 1975. The research, particularly in regard to collaboration with industry, has greatly expanded since then, as have the size and facilities of the laboratory, providing a number of important technology developments.

Legacy in fluid mechanics

In discussing Hawthorne’s work, an important aspect concerns his stamp on current fluid mechanics, in which numerical computations play a major role. Hawthorne’s work provided, from one perspective, analytical, approximate descriptions of the complex flows with which the gas turbine engineer must grapple. While such methodology has been superseded as the primary source of quantitative information, from another perspective his work was about *ideas*, *flow features* and *physical insight*; and providing these has grown in importance,

Figure 3. (*Left to right*) Sir John Horlock FRS, Sir Stanley Hooker FRS, Sir Frank Whittle FRS, Sir William Hawthorne FRS and Robert Feilden FRS at the opening of the SRC Turbomachinery Laboratory in 1973. (Photograph courtesy of Dr I. J. Day, Whittle Laboratory.)

especially in the development of effective design philosophies. We have mentioned this in the context of compressible flow, but we can add that communications and discussions about secondary flow (whether or not the motions are secondary to an assumed primary flow) are still couched in terms of vortex stretching and tipping. Actuator disks and their extension, embedded regions of body forces (referred to by Hawthorne as actuator ducts) are also in use, for example as a representation of turbomachinery within full aircraft Navier–Stokes computations. All these are part of his intellectual legacy.

Hawthorne's colleagues remember him as a generous and enthusiastic teacher who encouraged others to excel and as an engineer committed to his profession, imbued with a strong sense of duty and the belief that engineering could contribute to solving important problems facing humankind. They also recall his continuing interest, even in old age, in the institutions he served, and in new developments, ideas and issues.

Connections with MIT (1952–1996)

Hawthorne's links with MIT were longstanding and deep, even while a full-time member of the Cambridge faculty, and reached across several departments. His advisor, Professor Hottel, who was active past age 90, was from a chemical engineering background. He had long-term interactions with the mechanical engineering department professors Shapiro and Keenan; the latter was a major figure in shaping the curriculum in undergraduate thermodynamics in the US and elsewhere (see just below). He also had strong research collaborations with colleagues, including one of the authors, in the MIT Department of Aeronautics and Astronautics, with an office in the department's Gas Turbine Laboratory, where he was a co-supervisor on theses and a co-author on publications with students and faculty.

The level of Hawthorne's participation in the intellectual collaboration between the two universities, as well as his continued interest in thermodynamics and its teaching, can be seen in an anecdote related by Dr George Hatsopoulos, a co-founder of ThermoElectron Company (now Thermo Fisher Scientific), but back then, in the late 1950s, an assistant professor working in thermodynamics with Professor Keenan. One day Keenan told him, 'I've been invited to give lectures in England at Cambridge University. Come with me and give some lectures too.' Hatsopoulos was surprised to find out that not only were they teaching thermodynamics at the University of Cambridge from Keenan's book (*Thermodynamics*), but also that many aspects were aligned with ideas at the MIT Department of Mechanical Engineering. He asked Hawthorne about this: 'Professor Hawthorne, I'm very surprised that what you're doing in thermodynamics here sounds to me very much like what we're doing at MIT.' The response was simply: 'Mr Hatsopoulos, aren't you aware that Cambridge University was Keenanized . . . ?' (Hatsopoulos 2008).

In addition to the (many) informal visits that took place, Hawthorne had a strong formal relationship with MIT. He was appointed as the first Jerome C. Hunsaker Visiting Professor of Aeronautical Engineering in 1955–56, a Visiting Institute Professor (MIT's highest professorial rank) in 1962 and a member of the MIT Corporation, the governing body of the Institute, in 1969–74.

Hawthorne kept up active and fruitful collaborations with faculty and students at MIT for more than 40 years. He maintained that MIT and Cambridge working together offered advantages to both, and he followed this idea in both word and deed. At the memorial service for Hawthorne, Charles Vest, former president of MIT, noted that Sir William had suggested to Lord Broers (FRS 1986), one of Hawthorne's successors as Master of Churchill College and later Vice-Chancellor of the University of Cambridge, that 'he should meet the new president of MIT' and that this had resulted in a long-time friendship (Vest 2012). At a different level, and several decades earlier, one of the authors remembers a meeting including an opposite number at the other institution (now a career-long collaborator) in which Hawthorne delivered a short and heartfelt exhortation about the importance and benefits of close linkages between the two Cambridges. It is a pleasure to report that this view still prevails, that the technical and intellectual trans-Atlantic connections fostered by Hawthorne are still strong, and that the collaboration is still vigorous.

Hawthorne remained Hopkinson and ICI Professor at Cambridge until 1980. He served as a member of numerous government committees and advisory boards and continued as a consultant to industry long after he had retired from his academic appointments.

Some aerodynamic problems of gas turbine engines (1957)

One duty of the Hunsaker Visiting Professor role at MIT is to give a public seminar, the Minta Martin Lecture. Hawthorne selected 'some aerodynamic problems of aircraft engines' as his topic and presented a magisterial survey of problems with which engineers in the then-new jet engine field were grappling (4). It was a guided tour of 20 years of gas turbine research by a thought leader in the field. The paper gave insightful descriptions of the problems, the current understanding and the challenges, and it can still be read with profit for the clear description of phenomena. The topics are a ‘Who’s Who’ of issues still much with us: compressibility and choking, three-dimensional compressor and turbine design, secondary flow and generation of streamwise vorticity, rotating stall and compressor instability, combustion processes and shear layer mixing, and performance assessment of integrated propulsion systems.

Many of the questions Hawthorne posed in the paper have since been given much study, and we mention only two. One concerns a canonical fluid dynamic module, mixing of two streams. Time-averaged measurements he showed seem to indicate almost complete mixing followed by *unmixing*, with the temperature on the hot side becoming less than the spatial average and the temperature on the cold side becoming greater than the spatial average. The suggestion made is that complete mixing had *not* occurred because the measurements were the time-average of an unsteady vortical flow, with motion from one side of the duct to another. The discovery of vortex structures as a major feature of a mixing layer, reported in the early 1970s (Brown & Roshko 1974), show the insight of this suggestion. Hawthorne also called attention to the different levels of mixing for bulk momentum transfer and for the intimate mixing between molecules required for combustion, another point brought forward in later studies.

A second issue concerns the role of thrust and drag as metrics for aircraft performance, a question of current interest for boundary layer ingesting propulsion systems. Hawthorne remarked (in 1957!) that

> in the past it was possible to some extent to separate the activities of the engine manufacturer from those of the airplane manufacturer. We could distinguish between the positive force which it was the responsibility of the propulsion man to produce on the blades of the propeller . . . and the negative force on the rest of the aircraft, which the airplane man sought to reduce as much as possible.

He then points out that new developments in propulsion are making this distinction less easy and thus likely to eventually disappear (4).

He bolsters the arguments about thrust and drag with a model problem, the stovepipe ramjet portrayed in Figure 4 to illustrate the ‘forced nature of the distinction’. The upper figure (a) shows the streamlines for flow heating, i.e. combustion, and the lower figure (b) the streamlines for flow cooling, with the vertical dashed lines marking the region of heat addition or extraction. Hawthorne shows that thrust is produced with both heating and cooling and explains this as due to the very low pressure acting on the leading edge. He comments about the difficulties, both semantic and engineering, in reconciling the task of the propulsion engineer, concerned with flow through the body, with that of configuring the leading edge to avoid flow separation. He also poses the problem of distinguishing between thrust and drag if one side of the ramjet were omitted and the propulsion system were part of the vehicle boundary. This now occurs in boundary layer ingesting aircraft, leading to new ways (perhaps not to Hawthorne) to describe propulsion system performance using a power balance rather than in terms of forces. The paper ends with a strong recommendation to avoid the ‘rigidity of thought which stems from trying to compartmentalize our ways of thinking’—excellent advice then, and even more relevant for the highly integrated air-breathing vehicles being considered today.

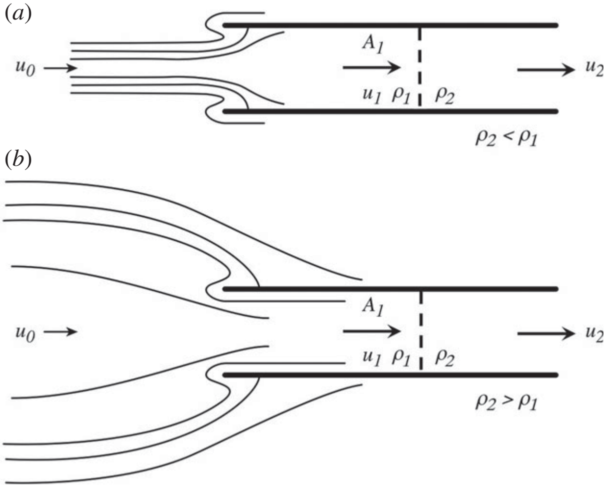


Figure 4. Flow through stovepipe ramjet, showing flow around leading edge, implying production of thrust (a) with heat addition, and (b) with heat extraction (cooling). (Adapted from (4) with permission.)

MASTER OF CHURCHILL COLLEGE (1968–1983)

Several months after Hawthorne was appointed as head of the engineering department he became the second Master of Churchill College; a new college at Cambridge, founded in 1960 with focus on natural or medical sciences, engineering and mathematics (70% of the students and academic staff are in these fields). The college was created, with substantial support from Commonwealth countries and the United States, as a memorial to Sir Winston Churchill, and the Mastership is a crown appointment. There was initial concern within the fellows of the college that the duties of the new Master might be restricted by his responsibilities as department head, but this proved to be unfounded, in part because Hawthorne had the ability to work continuously for long hours, with only a few hours' sleep each night. He had a huge range of interests and regularly chaired late evening discussions in the college. His formula for these discussions was simple: have a good dinner with a dozen or more colleagues and guests and then hold a discussion. These events sometimes lasted into the small hours, but Hawthorne never flagged during marathon discussions, especially on subjects that interested him.

One such subject was the supply of engineers to industry and their practical training. Hawthorne wanted graduate training to be more organized and motivational than he had experienced at Babcock & Wilcox. His ideas and enthusiasm led to a new approach to practical training. Traditional hands-on experience was supplemented by guided projects, discussions, seminars and talks. Experimental courses held on his initiative in the 1950s led eventually to the University of Cambridge advanced course in production methods and management, which developed into an MPhil course in the engineering department's Institute for Manufacturing.

Churchill College has had a small cadre of visiting Overseas Fellows, Industrial Fellow Commoners, and others, living at the college. As Master, Hawthorne took an interest in those visitors and did his best to make them and their families feel welcome, from encouraging participation in college activities, to arranging for weekend walks with spouses and children invited. These outings ranged from scenic walks on top of dikes, to Wandlebury and the Gog Magog Hills, to visits to industrial archaeology sites such as the Stretham Old Engine (a steam-powered engine built in 1831 that pumped water from flood channels in the River Great Ouse), and the Grimes Graves prehistoric flint mines. The end of the series of weekly walks was a ramble along the 'Duke of Grafton's Ride' followed by a grand picnic with much of the cooking and provisions supplied by Hawthorne.

Despite Hawthorne's many professional activities, he was active and popular, known for his support for the rowing club and for musical activities, and also as a gracious host for the many visiting scholars. The College's Archives Centre, which he was instrumental in creating, now houses the papers of Winston Churchill, Margaret Thatcher and many other distinguished political and military personalities. He remained as Master until 1983.

Awards and honours

Hawthorne was elected a Fellow of the Royal Society in 1955, appointed CBE in 1959 and knighted in 1970 for 'services to thermodynamics', a citation that greatly pleased him; in this regard he has been described as 'the first knight of the second law of thermodynamics' (Goldie & Squire 1993). He was a founding Fellow in 1976 of the Fellowship of Engineering (later the Royal Academy of Engineering), a Fellow of the Institution of Mechanical Engineers, the Royal Aeronautical Society and other professional bodies. He was elected Foreign Associate of both the US National Academy of Science and the National Academy of Engineering, and was Honorary Fellow of several professional societies, including the American Institute of Aeronautics and Astronautics and the Royal Aeronautical Society, and was an Honorary Member of the American Society of Mechanical Engineers. He was elected Honorary Fellow of Trinity College in 1995.

He was twice vice-president of the Royal Society (in 1969–70 and 1979–81), and in 1982 received its Royal medal. As vice-president he led the first Royal Society visit to post-war China, during which he entertained the staff and passengers of the train he was travelling on with a magic show. He held honorary degrees from the universities of Sheffield (1976), Salford (1980), Strathclyde and Bath (both 1981), Liverpool and Oxford (both 1982), and Sussex (1984).

Advisor to government and industry

Hawthorne was sought after as an advisor to the British and American governments on a broad range of defence, energy and security questions. Of these, we mention only his chairmanship of the Home Office Scientific Advisory Council, in which he was active for almost a decade.

In the context of US industry, Hawthorne had a long relationship with Cummins Engine Company in Indiana. He was a director from 1974 to 1986 and carried out research on turbochargers with Cummins and with their British subsidiary, Holset, until the age of 85. He is credited with giving technology and research a more significant role. He was also a long-time consultant to Pratt & Whitney, the jet engine manufacturer, and he helped shape the direction of their early work on three-dimensional compressor flows.

HOBBIES

Hawthorne’s hobbies included walking, skiing, sailing, cookery, the theatre and conjuring. Another hobby lay in his appreciation of science fiction, starting as a young admirer of the works of H. G. Wells. For many years he was a subscriber to *Astounding Science Fiction*, and he would reflect with colleagues on the feasibility of some of the ideas advanced therein.

He was a member of the University of Cambridge Pentacle Club from his undergraduate days onwards, and for 20 years was its president. His skill as a magician entertained and enthralled his colleagues at Churchill College and at MIT on several occasions. He celebrated his seventieth and eightieth birthdays with conjuring shows on both sides of the Atlantic. A high point of the latter was his demonstration of sawing a young woman in half and then joining her together again—it was reported as the most ambitious and spectacularly successful postprandial talk ever to be held in Churchill College’s Senior Combination Room.

The masterful execution of the conjuring was complemented by his professional level of ‘patter’, which aided the misdirection and heightened the illusions. We give two examples. The first was in connection with sawing a woman in half and was presented as an offhand joke:

> First magician to second magician: ‘Who was that lady I sawed with you last night?’
> Second magician to first magician: ‘That was no lady, that was my half-sister.’

The second was the (extremely well-developed) knack of dissembling in the completion of a trick so it appeared that things were not going well, and then, to the surprise and delight of the audience, snatching victory out of the jaws of defeat, often with (again) an appropriate patter line. One of the authors was at a dinner with 20 engineers from a diesel engine company, where Hawthorne was apparently having difficulty making something by tearing up coloured tissue paper. While apparently fumbling and stating apologically that he was sorry he had made such ‘a bloomer out of this’, he then proceeded to pull, with an air of triumph that told the onlookers all was well, a bloomer-like garment out of the tissue paper, accompanied by the words ‘in fact, I had made a pair of bloomers’. Both authors have tried, on more than one occasion, to sit close enough to diagnose the actual sequence of events, but we were no wiser at the end of the illusion.

Hawthorne died at his home in Cambridge, England, on 16 September 2011, of bronchopneumonia following a stroke. He was buried next to his wife in the family plot in the Mayflower cemetery in Duxbury, Massachusetts. Memorial events were held in Cambridge on 24 February 2012 and at MIT on 24 March 2012. At the MIT service, two former MIT presidents gave their remembrances and the service was followed by a tour of the MIT Gas Turbine Laboratory. At the Cambridge memorial, the service was followed by an entertainment organized by the Pentacle Club celebrating ‘our late member, former President, and fellow magician Sir William Hawthorne’.

His wife, Barbara Runkle, of Cambridge, Massachusetts, died in 1992. Their children, Alexander, Joanna Amick and Elizabeth O’Beirne-Ranelagh, grandchildren, Alexandra Amick Vrazo and Charles Amick, and great-grandson, Julian Rede Vrazo, survive them.

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Edward M. Greitzer is the H. N. Slater Professor and interim head (2018) of the Department of Aeronautics and Astronautics at MIT, where he has also been a director of the Gas Turbine Laboratory. He received his BA, MS and PhD from Harvard. In addition to his experience in academia, he worked at United Technologies Corporation for roughly a decade, both at the Pratt & Whitney division and at the United Technologies Research Center. His research interests include gas turbines, turbomachinery, propulsion system–airframe integration, active control of fluid systems and industry–university collaboration. He is the lead author of the book *Internal flow* (Cambridge University Press). He was the MIT lead on the Cambridge–MIT Silent Aircraft Initiative and has had several term- and year-long stays at Cambridge. His host for the initial stay in 1975, as an Industrial Fellow Commoner, was Sir William Hawthorne. For several years Professor Greitzer shared an office with Sir William during the latter's frequent visits to MIT. They also shared a strong interest in turbomachinery fluid flow and in linkages between the two Cambridges; these interests have continued throughout Greitzer's career.

David E. Newland

David E. Newland is an Emeritus Professor of Engineering at the University of Cambridge. When an undergraduate, he attended lectures and, in his third year, weekly supervisions by Hawthorne. Subsequently he became a research assistant for Hawthorne's Dracone Project of 1957. Newland worked in industry before taking his PhD at MIT and becoming an assistant professor there in the 1960s. He has also taught at Imperial College London and the University of Sheffield, specializing in mechanical engineering design. His commissions included: bogie design for the Canadian Turbotrain; isolating buildings from underground train noise in London; and taking part in de-wobbling the London Millennium footbridge in conjunction with Arup in 2000–02. Forensic design studies included the Flixborough chemical plant explosion of 1974 and Piper Alpha oil rig disaster in 1988. He was a founding member of the Cambridge Engineering Design Centre and is a former head of the University of Cambridge engineering department. He is a fellow of Selwyn College.

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