Osborne Reynolds: the Turbulent Years

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ABSTRACT

The paper summarizes aspects in the life of Osborne Reynolds, FRS, with particular attention to: his appointment to the newly established Chair of Civil & Mechanical Engineering at Owens College Manchester in 1868; hitherto unreported aspects of his personal life concerning his second marriage; and the period from 1883 to 1895 during which his pioneering and much cited papers on turbulent flow were published, despite in one case strong criticisms from the referees. The paper also examines Reynolds' unsuccessful applications in 1884 for professorships in London and Cambridge. The former was for a position requiring a major organizational role which, had his application succeeded, may well have prevented his Reynolds-decomposition analysis from being written.

Keywords: Horace Lamb, Lord Rayleigh, Osborne Reynolds, Reynolds decomposition, Sir George Stokes, William Cawthorne Unwin

1. INTRODUCTION

1.1. Early Years

Accounts of Osborne Reynolds' life and works have appeared in numerous articles beginning with a remarkably perceptive obituary notice published in *Nature* within eight days of his death and a similar, more extensive account by Sir Charles Lamb, FRS published by the Royal Society, [1]. More recent reviews have been provided by Gibson[2] a student and, later, an academic colleague of Reynolds, by Allen[3], who provided the leading article in a volume marking the passage of 100 years from Reynolds taking up his chair appointment in Manchester and by Jackson [4] in an issue of *Proc. Roy. Soc.* celebrating the centenary of the publication of Reynolds' paper, [5], on what we now call the "Reynolds decomposition" of the Navier-Stokes equations (leading to the *Reynolds equations* in which the *Reynolds stresses* appear as unknowns). A good deal more will be said about this last paper later in the present article. It is appropriate, however, that we should begin with a brief summary of Reynolds' life that preceded the turbulent and momentous years providing the centre-piece of this article. While inevitably, much of what is presented below will be known to those who have read one or more of the cited works above, archive material held by the University of Manchester and The Royal Society provides new perspectives on parts of his career.

Osborne Reynolds was born on August 21st, 1842 at 3 Donegall Place, Belfast adjacent to the 1st. Belfast Collegiate School where his father, the Revd. Osborne Reynolds, was for a short time Principal. Despite the brevity of the family's stay in Ireland, at least two Irish history websites include Osborne Reynolds in their listings of famous Irishmen (lists that also include Sir George Stokes and Lord Kelvin, the former of whom will play a significant role later in this account). In fact, in 1843 the family moved to Chesham in Buckinghamshire where the Revd. Reynolds had obtained a position as curate. However, in 1844 his wife died in the delivery of their third child (the eldest progeny, Jane, had been born in 1840) leaving him a widower with three small children to care for (J.D.Jackson, personal communication). In the wake of this family tragedy he succeeded in obtaining the position as head-master of Dedham Grammar School, in Essex, Fig. 1. There young Osborne spent his early years being tutored initially by his father who had himself read Mathematics at Cambridge and had developed a strong interest in practical mechanics. In 1848 his grandfather who (like *his* father before him) was rector of Debach in Suffolk died and his father, who already owned a farm near the village, stepped in as temporary replacement rector, a responsibility he discharged in parallel with his duties as headmaster at Dedham, (J.D.Jackson, personal communication).

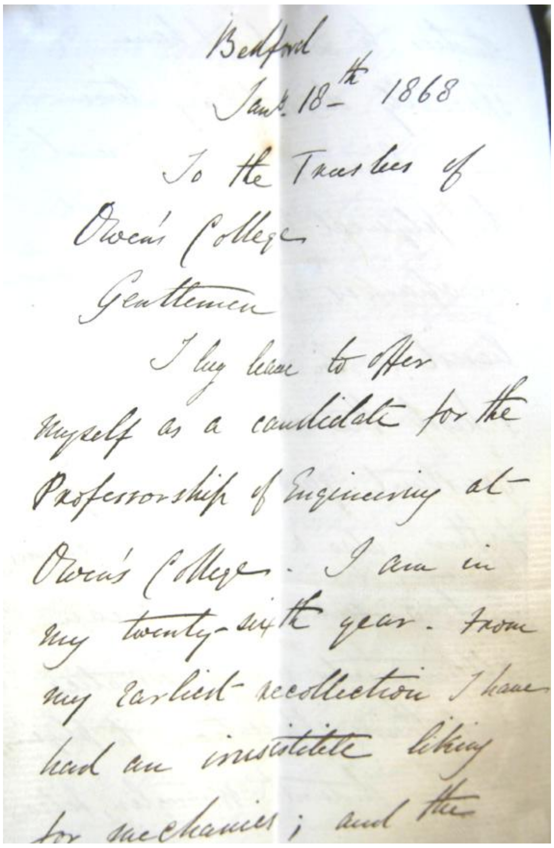
Figure 1: The Old Schoolhouse, Dedham (a) in Reynolds' time (b) today

At the age of nineteen Osborne Reynolds, having acquired equally as strong a fascination for mechanics as his father, left home to join the engineering workshop of Edward Hayes, a mechanical engineer of Stoney Stratford, where typically a dozen apprentices (or, perhaps more accurately, the sons of middle-class country families) would be taking their first steps in learning the rudiments of mechanics. Reynolds' object in taking this placement, as explained later in a testimonial for him by Mr Hayes, was '*to learn in the shortest time possible how work should be done and, as far as time would admit, to be made a working Mechanic before going to Cambridge to work for Honours*' (UoM Arch). In 1863 Reynolds was duly admitted, like his father, to Queens' College, whence he graduated with a BA in 1867 as seventh Wrangler. This level of distinction did not come easily, however, as a quotation from his tutor below shows. Thereafter, he took up employment with Lawson & Mansergh, in London but within a few months news reached him that Owens College, Manchester had advertised the creation of a Professorship in Engineering. On January 18th, 1868 he duly wrote a letter of application that begins (UoM Arch):

"*Gentlemen,*

I beg leave to offer myself as a candidate for the Professorship of Engineering at Owen's [sic] College. I am in my 26th year. From my earliest recollection I have had an irresistible liking for mechanics; and the studies to which I have especially devoted my time are mechanics and the physical laws on which mechanics as a science are based. In my boyhood I had the constant guidance of my father, also a lover of mechanics and a man of no mean achievement in mathematics and their application to physics."

The hand-written opening of this letter is shown in Fig. 2.



Bedford
Jan. 18th 1868
To the Trustees of
Owen's College
Gentlemen
I beg leave to offer
myself as a candidate for the
Professorship of Engineering at
Owen's College. I am in
my twenty-sixth year. From
my earliest recollection I have
had an irresistible liking
for mechanics; and the

Fig. 2: The opening of Reynolds' letter of application

1.2. Chair application at Owens College

Much has been made of Reynolds' youth and (thus) his audacity in applying for the Chair and, equally, the wisdom of the appointing committee (which included William Fairbairn and Joseph Whitworth) in choosing him. It is seen from Table 1, however, that Reynolds was by no means the youngest candidate. In the 1860's, knowledge of Mechanics and a vision of where it might lead must have been as much an area where the real experts were still in their twenties as certain aspects of software engineering are today.

The Chair was initially advertised at a salary of £250 per annum. Eighteen applications were received, Table 1, including Reynolds' and that of Mr William Cawthorne Unwin who will also appear later in this account. This last named felt he must have a good chance as he had been assured of strong support from his former employer and one of the selection committee, William Fairbairn. The procedure was for candidates to submit their supporting reference letters and in Reynolds' case, at least, the hand-written letters (of which there were around a dozen) were complemented by a printed version of the same and of the letter of application itself. Reynolds' letters included one from Mr Hayes from which the quotation above has been taken, another from Archibald Sandeman, then Professor of Mathematics at Owens but who had formerly been Reynolds' tutor at Queens' College plus three others from Cambridge staff: a cursory note from James Clerk Maxwell, FRS confirming Reynolds' standing in the graduating list, and more fulsome communications from J. C. Challis, FRS, Professor of Astronomy and the mathematics tutor, John Dunn who commented that while on entry he had lacked knowledge in mathematics "*by innate talent and undeviating perseverance Mr Reynolds made the most rapid progress*". Perhaps most surprisingly to a 21st Century reader, possibly connected with his son's reference to him in his letter of application, the Reverend Osborne Reynolds also provided a reference, a task which, his words suggested, had surprised and embarrassed him. He nevertheless praised his son's qualities and concluded: "*The only point I can conceive against him is his youth – he is only in his 26th year. But this is compensated for by his early devotion to Science and the practice of his profession*"

Despite the large numbers of applications the minutes of a meeting of the Owens Committee of Trustees on January 30th 1868 reported the appointing committee's disappointment at their quality. However, Mr Charles F. Beyer, a German who had come to Manchester as an impecunious young man to make his fortune (and had!) offered to provide sufficient further funds to enable the post to be re-advertised with "*...an additional £250 p.a. for the first five years in the hope that the increased remuneration would enable the Trustees to obtain applications from gentlemen of higher scientific attainments and greater professional experience than could be expected under the moderate inducements held out in the advertisement.*" A further eleven applications were received to the re-advertisement with its upgraded salary and there had clearly been discreet contact with Professor Rankine at Glasgow University who, after initially showing some interest, chose not to pursue the matter. Thus the Trustees decided to interview "*Mr George Fuller, C.E., Associate of the Institution of Civil Engineers and Mr Osborne Reynolds, B.A., Fellow of Queens' College, Cambridge whom they believe to be the most eligible*". Both interviewees, it is noted, were drawn from the original list of applicants: with Rankine having finally declined to become a candidate, the increased offer had served nothing other than to double the salary of the successful candidate. As the world of Fluid Mechanics gives thanks, that candidate was Osborne Reynolds!

Table 1: Applicants for Owens Chair in Engineering (transcribed from the manuscript document, UoM Archive)

No.	Camdidate Name	Age
1	Samuel Downing	L
2	Francis Albert Ranken	28
3	Cameron Knight	38
4	William O'Brien	37
5	Paul R. Hodge	55
6	Edward Sang	63
7	George Ross	L
8	Goodwin White	22
9	**Osborne Reynolds**	**25**
10	E. Nugent	45
11	**William Cawthorne Unwin**	**29**
12	George Fred[ck] Armstrong	
13	Joseph Pythian	24
14	Wm James Villiers Semtey	45
15	**George Fuller**	**38**
16	James MacCallum	25
17	J. J. Montgomery	35
18	George F. Deacon	24
	Applicants from the 2nd announcement	
19	Thomas Cargill	32
20	E. C. Farley	22
21	William Henry Knapp	27
22	Thomas Box	46
23	Walter West	33
24	Thomas John Crosthwait	28
25	James N. Shoolbrest	
26	Arthur Smith Truman	34
27	W. J. Ellis	31
28	William Edmund Rich	28
29	John Anstie	28
	L= Application for Lectureship	

As for W. C. Unwin, as soon as the Trustees' decision had been reached, his former employer wrote to him, Walker [6]:

"*My dear Unwin,*

I am very sorry I cannot forward to you the agreeable intelligence that you are elected to the position of professor. I so earnestly wished for you to occupy that position. It would have exactly suited your tastes, and I had every reason to believe you would have been an active and excellent professor.……In wishing you better luck in your next undertaking, I am,

Yours,

Wm. Fairbairn."

Walker's commissioned biography of Unwin, [6], as works of that kind inevitably are, was staunchly supportive of its subject. Ignoring the fact that Unwin was not one of those invited for interview, it nevertheless chose to present the chair appointment as a contest between Unwin and Reynolds that involved at least misjudgement by the interviewing committee and perhaps political intrigue to boot, [6]:

"*Bearing in mind the researches on materials and on bridge design which he at that time had recently completed ….it is certainly remarkable that no better reason could be adduced by the College authorities for passing over Unwin in favour of one whose experience of civil engineering was less, and whose fame rests upon his work as a physicist rather than as an engineer. Owen's [sic] College at that date was, to a very great extent, a municipal undertaking and one cannot help thinking that, in the lively atmosphere that surrounded its early development, considerations other that academic may have played some part in the deliberations of the Senate.*"

It is noted for the record that none of the documents seen in the University of Manchester's archives lends any support to Walker's insinuation that "considerations other than academic may have played some part" in the decision. The creation of the Chair was the outcome of leading industrialists from Manchester recognizing the need to underpin the region's industrial strengths with a skilled and knowledgable professional workforce. Moreover, few if any would agree with his suggestion that Reynolds' subsequent "fame" (which in any event the appointing committee could hardly be expected to foresee) was due to his contributions as a physicist rather than as an engineer. As Reynolds' pioneering contributions have abundantly made clear, however, engineering break-throughs habitually require a mind possessing deep physical insight!

2. PROFESSORIAL CAREER

2.1 The First Decade

The year 1868 must have been one that brought Reynolds immense pleasure, for shortly after his success at the Chair interview he married Charlotte, the daughter of Dr Chadwick from Leeds. However, the associated joy was short-lived for his wife died in July the following year, Allen [3], leaving Reynolds with the grief and isolation of widowerhood accompanied by the responsibilities of bringing up his new-born son. Neither Allen, nor any other of the sources consulted, records whether Charlotte died in, or as a direct consequence of, child-birth. Clearly, however, these personal events posed a difficult beginning for Reynolds' career, even if eased by his deep religious beliefs.

At the time of his appointment Owens College (which had been founded in 1851 following a generous bequest by John Owens) occupied a building on Quay Street, the former home of Richard Cobden, the distinguished MP for nearby Stockport which is now restored and houses solicitors' offices, Figure 3. In 1868, however, it had little in the way of laboratory facilities for either teaching or research, [4]. Indeed, even after the removal of the College to the present site of Manchester University in 1873 there was initially limited scope for experimental work. This explains why Reynolds' early research was concerned largely with explaining external natural phenomena: what J. J. Thomson, his most famous student, later termed 'out-of-door physics'. The work falling under this head has been well summarized in [4] while the papers themselves all appear in Volume I of Reynolds' collected works, [7]. The tails of comets, the solar corona and the aurora form the subjects for the first papers in this group followed by suggestions of the inductive role of the sun on terrestrial magnetism and the electrical properties of clouds.

Figure 3: Owens College Building at 19, Quay Street, as currently arranged.

The first from this group of papers involving the thermo-fluid dynamics of liquids concerned the bursting of trees struck by lightning, which by experiment he attributed to the rapid vaporization of fluid within the trunk. Thereafter Reynolds tackled such topics as the calming of seas both by raindrops and by the spread of an oil film on the surface and the formation of raindrops, hailstones and snow flakes. For these studies he contrived simple but effective experiments on a small enough scale for them to be undertaken with the limited laboratory facilities available. Diagrams of the apparatuses from the original papers are reproduced in [4].

In the second half of the 1870s his fluids research underwent a shift towards more general phenomena such as the progression of dispersive surface waves in deep water and the motion of vortices, the latter made visible by coloured dye traces in water. In this period he also provided two papers on heat transfer, one considering the effect of mixing air with steam on the condensation rate at a wall while the other implied links between skin friction and heat transfer rate; effectively, what is known today as *Reynolds Analogy*. Other more applied fluid dynamics research from the 1870s include studies into the racing of ships' screw propellers (which he showed was a consequence of the admission of air) and a detailed patent specification for improving the performance of turbines and centrifugal pumps. Regarding this latter work, Gibson [2] has remarked that it anticipated both the multi-stage Parsons turbine and the contra-rotating stages of the Ljungstrøm turbine.

In recognition of the huge research contributions made within the decade following his appointment, in 1877 Osborne Reynolds was admitted to Fellowship of the Royal Society of London.

2.2 New Beginnings

Soon after the start of his second decade as the Professor of Mechanical & Civil Engineering, Reynolds suffered a personal tragedy analogous to that which followed his original appointment. His son, the ever present reminder of his deceased wife, died in 1879 [3]. Two years later, however, he married Annie Charlotte, daughter of the Revd. Henry Wilkinson, rector of Otley in Suffolk. No account has been found of how the couple met but it is noted that Otley was the parish next to Debach-with-Boulge where Osborne Reynolds' father, continued the tradition, set by *his* father and grandfather before him, by temporarily becoming rector of that parish and thereafter settling permanently in Debach House a manor with some 160ha of land attached (J. D. Jackson, personal comunication). It is likely that in such small rural communities there would have been extensive social interactions among the middle-class families. Annie was born in December 1859 so there was an age difference of seventeen years between them.

Figure 4: The Reynolds' family home at 23, Lady Barn Road, Fallowfield.

Although there would seem no practical reason why the newlyweds could not have lived in Reynolds' existing house, there were evidently strong emotional reasons, given what had gone before, for them starting afresh in brand-new surroundings. New red-brick, semi-detached houses were then being built on Lady Barn Road, about two miles from the College, and Reynolds purchased No. 23 where they lived for the remainder of their time in Manchester. (The house still exists in broadly its original external form, Fig 4, though internally it has now been divided into two apartments.) Their marriage appears to have been a happy one with three sons and a daughter resulting from their union.

2.3 The Turbulent Flow Papers

With his personal life having undergone such a pleasurable and satisfying transformation and, at a practical level, with Annie available to take charge of household management, Reynolds directed his research at larger-scale research preoccupations. While it was by no means his only subject of interest, the present account examines just his contributions to turbulent flow. This draws extensively from an earlier version contributed by the author to the paper by Jackson & Launder [8]. Although the principal attention will be on the later analytical study, [5], we first consider the experimental investigation as the discoveries in that paper both shaped the later publication and, moreover, had a significant impact upon a referee who was called on to review each of the papers.

2.3.1 The 1883 Paper

Readers will certainly be familiar with the apparatus used in Reynolds' study into (to quote from the title of his *Phil Trans Roy Soc* paper [9]) "*the circumstances which determine whether the motion of water shall be direct or sinuous*". The original print of the tank has been reproduced in numerous articles and text books while Figure 5 shows a photograph of the apparatus today in the author's School at the University of Manchester. The glass tube with flared entry which is itself housed within a tank filled with water still offers students a very clear indication of the starkly contrasting states of motion, whether '*direct*' or '*sinuous*' (or, in today's terminology, *laminar* or *turbulent*). In Reynolds' own words: '*The internal motion of water assumes one or other of two broadly distinguishable forms – either the elements of the fluid follow one another along lines of motion which lead in the most direct manner to their destination, or they eddy about in sinuous paths the most indirect possible*'. Reynolds' dye-streak studies showed that, for a range of flow velocities, pipe diameters and viscosities, transition from the former mode to the latter occurred for roughly the same value of a dimensionless parameter which today bears his name.

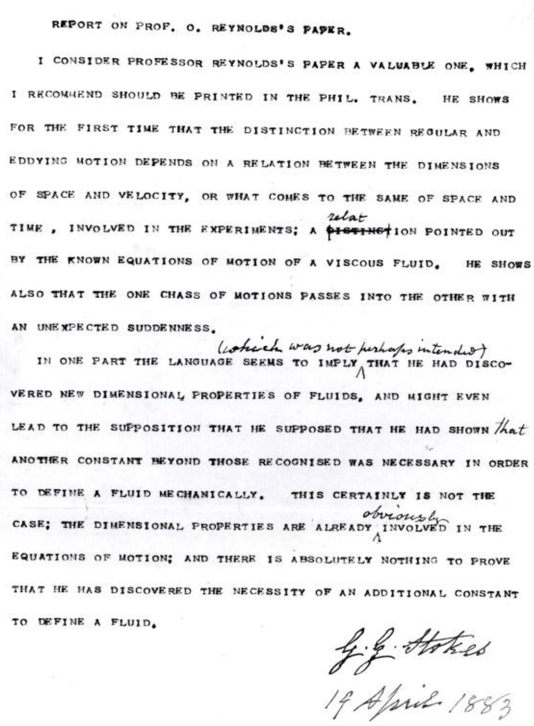
The first step in Reynolds' discovery of this parameter appears to have been his observation that '*the tendency of water to eddy becomes much greater as the temperature rises*'. It occurred to him that this might be related to the fact that the viscosity of water diminished as the temperature rose. By examining the governing equations of motion he concluded that the forces involved were of two distinct types, inertial and viscous, and further that the ratio of these terms was related to the product of the mean velocity of the flow and the tube diameter divided by the kinematic viscosity. In his paper he states:

'*This is a definite relation of the exact kind for which I was in search. Of course without integration the equations only gave the relation without showing at all in what way the motion might depend upon it. It seemed, however, to be certain, if the eddies were due to one particular cause, that integration would show the birth of eddies to depend on some definite value of* [that group of variables]'.

Figure 5: The Osborne Reynolds tank today, School of MACE, U. Manchester

He recognized, however, that the critical value thus arrived at (sometimes called the '*higher critical number*') was not unique as it was affected strongly by the level of background disturbances present. In a second series of experiments he thus set about determining the value of Reynolds number below which highly turbulent motion created at entry to the pipe decayed to laminar flow. In this case, in a different apparatus, he used pressure drop measurements to delineate the mode of flow. Although Reynolds, in that paper, never cited the actual values, Allen [3] concluded from the figures that he *did* quote that, for the two lead pipes used in this second set of experiments, the '*lower critical number*' was 2010 and 2060 while, in his later paper, Reynolds [5] put the critical value between 1900 and 2000.

The two referees of the manuscript that Reynolds submitted to The Royal Society were the considerable figures of Sir George Stokes and Lord Rayleigh, each of whom was broadly supportive of publication. Stokes was a pioneer in the use of the typewriter though it appears that the machine he used for his review had available only upper-case letters, Figure 6, and that the process of typing was sufficiently demanding that, rather than re-typing a final version, he chose to insert by hand his subsequent embellishments and corrections (though he failed to correct CHASS in the first paragraph).



REPORT ON PROF. O. REYNOLDS'S PAPER.

I CONSIDER PROFESSOR REYNOLDS'S PAPER A VALUABLE ONE, WHICH I RECOMMEND SHOULD BE PRINTED IN THE PHIL. TRANS. HE SHOWS FOR THE FIRST TIME THAT THE DISTINCTION BETWEEN REGULAR AND EDDYING MOTION DEPENDS ON A RELATION BETWEEN THE DIMENSIONS OF SPACE AND VELOCITY, OR WHAT COMES TO THE SAME OF SPACE AND TIME, INVOLVED IN THE EXPERIMENTS; A ~~DISTINCT~~ relatION POINTED OUT BY THE KNOWN EQUATIONS OF MOTION OF A VISCOUS FLUID. HE SHOWS ALSO THAT THE ONE CHASS OF MOTIONS PASSES INTO THE OTHER WITH AN UNEXPECTED SUDDENNESS.

IN ONE PART THE LANGUAGE SEEMS TO IMPLY (which was not perhaps intended) THAT HE HAD DISCOVERED NEW DIMENSIONAL PROPERTIES OF FLUIDS, AND MIGHT EVEN LEAD TO THE SUPPOSITION THAT HE SUPPOSED THAT HE HAD SHOWN that ANOTHER CONSTANT BEYOND THOSE RECOGNISED WAS NECESSARY IN ORDER TO DEFINE A FLUID MECHANICALLY. THIS CERTAINLY IS NOT THE CASE; THE DIMENSIONAL PROPERTIES ARE ALREADY obviously INVOLVED IN THE EQUATIONS OF MOTION; AND THERE IS ABSOLUTELY NOTHING TO PROVE THAT HE HAS DISCOVERED THE NECESSITY OF AN ADDITIONAL CONSTANT TO DEFINE A FLUID.

G. G. Stokes
19 April 1883

Figure 6: Sir George Stokes' review of 1883 paper

Lord Rayleigh's review dated March 30/83 (Roy. Soc. Archive Ref.183) was spread over three pages but amounted to only 70 words. The first sentences gave his lofty, rather patronizing observation and verdict:

'*This paper records some well contrived experiments on a subject which has long needed investigation – the transition between the laws of flow in capillary tubes and in tubes of large diameter as employed in Engineering. I am of opinion that the results are important, and that the paper should be published in the Phil. Trans.*'

It then concluded: '*In several passages the Author refers to theoretical investigation whose nature is not sufficiently indicated. Rayleigh*'.

The paper was duly published and, in the years that followed, each of the referees publicly signalled the exceptional importance of Reynolds' paper. First, Lord Rayleigh, in his 1884 Presidential Address to the British Association in Montreal, paid the following tribute:

'*Professor Reynolds has traced with much success the passage from one state of things to the other, and has proved the applicability under these complicated conditions of the general laws of* *dynamic similarity as adapted to viscous fluids by Professor Stokes. In spite of the difficulties which beset both the theoretical and experimental treatment, we may hope to attain before long to a better understanding of a subject which is certainly second to none in scientific as well as practical interest*'

Sir George Stokes served as President of the Royal Society from 1885 to 1890 and in this capacity, in November 1888, he presented the Society's Royal Medal to Osborne Reynolds '*for his investigations in mathematical and experimental physics, and on the application of scientific theory to engineering*'. More than half of Stokes' citation was devoted to a summary of the 1883 paper.

2.3.2 A passing fancy

Besides the immediate acclaim accorded his 1883 paper, the recent agreeable developments in his personal life (his marriage, the purchase of his new home and the safe delivery of Henry Osborne, the first of the four children he was to have with Annie) not to mention his admission in 1882 as an Honorary Fellow of Queens' College Cambridge, would, one might have supposed, have suppressed the desire, on his part, for bringing about any major upheaval in his life.

However, the Livery Companies of the City of London and the City Corporation, concerned at the limited provision in the capital of facilities in engineering, formed the City & Guilds of London Institute [6] which secured a site in South Kensington where the Central Institution of the Institute was built (from 1910, known as the City & Guilds College, one of the constituent colleges of Imperial College). When the building was nearing completion, at the beginning of 1884, steps were taken to appoint key staff. Reynolds decided to apply for the advertised Chair in Civil & Mechanical Engineering and, unsurprisingly, made the short-list along with W. C Unwin, who following his disappointment in Manchester had, in 1872, been appointed to a chair at Cooper's Hill College, and A. B. Kennedy, a professor at University College, London [6]. On this occasion, however, reversing the Manchester decision, it was Unwin who was the successful candidate.

It is worthwhile pausing to reflect on the likely consequences for Fluid Mechanics if, instead, Reynolds had been appointed to the Chair. The building was new but unoccupied and presumably unequipped (since the professors would have been responsible for choosing the equipment for their laboratories). The first students were admitted in February 1885 from which time Unwin was appointed Dean of the Institution, with all the associated administrative responsibilities, on top of the task of teaching in his own department without, initially, any demonstrators or assistants [6]. Thus, it seems at least questionable whether, had Reynolds been chosen for that position, his major remaining works on fluid mechanics and thermodynamics would have been written, at least in the form we know them. The papers that would have been placed in jeopardy included not only his follow-up to the 1883 paper to which we shall shortly turn but also his comprehensive paper on film-lubrication published in 1886, Reynolds [10], in celebration of which, 100 years later, an international conference was held, Dowson et al. [11].

Reynolds' disappointment at failing to secure the chair in London must have been assuaged that summer, by the conferment of an honorary degree by the University of Glasgow, where W. J. M. Rankine had formerly been a professor and where the Thomson brothers (James, Rankine's successor, and Sir William [later Lord Kelvin]) then served. Whether this last distinction had any bearing on his subsequent action is unknown but, later that year, he applied for the vacant Cavendish Professorship of Experimental Physics at Cambridge. Despite Reynolds' numerous distinctions, however, the appointment went to his former student, J. J. Thomson (then a young man of 27 but later, Sir Joseph Thomson, OM, Nobel Laureate and President of the Royal Society). Although it has already been quoted [2, 3], it is worthwhile repeating Reynolds' generous letter of congratulations sent on Boxing Day, 1884:

"*My dear Thomson,*

I do not like to let the occasion pass without offering you my congratulations, which are none the less sincere that we could not both hold the chair. Your election is in itself a matter of great pleasure and pride for me… and I have no doubt but every hope that you will amply justify the wisdom of the election. Believe me, Yours sincerely

Osborne Reynolds"

Thus, Osborne Reynolds remained at Manchester. But what had provoked this desire to leave? A colleague has suggested his new wife may have applied pressure for them to move to a more attractive urban environment; but this seems unlikely given that she had become settled in Manchester and, as a Victorian woman barely in her mid-twenties, would surely have deferred to the wishes of her husband on all things relating to his professional life. It seems more likely that the decisions were Reynolds' alone, perhaps feeling frustrated that, after sixteen years in post, he still did not have at his disposal laboratory facilities competitive with those elsewhere in the country. Indeed, Thompson [12] (as reported by Allen [3]) notes that in that year (1884) Reynolds drew the attention of Council to the urgent need for an engineering laboratory. It seems that, finally, this overdue complaint may well have led in 1887 to the provision of state-of-the-art laboratories, [2].

2.3.3 The 1895 Paper

As the preceding section has indicated, in the years following publication of the 1883 paper the unresolved questions stimulated by his discoveries by no means fully occupied Reynolds' mind. Perhaps for that reason, only in 1894 did he feel ready to respond to Lord Rayleigh's expressions of hope for progress on the theory, reporting orally the results of his extensive analysis to the Royal Society on May 24th. Thereafter he submitted a written version of this work that he had had printed at his own expense to be reviewed for publication in the Phil Trans. By then Reynolds, of whom a contemporaneous photograph appears in Figure 7, had held his Chair for more than 25 years, had been a Fellow of the Royal Society for more than fifteen and, as noted above, had received numerous awards. He was then arguably the leading engineering fluid mechanicist in England and possibly more widely than that.

Figure 7: Osborne Reynolds c.1895

Lord Rayleigh had meanwhile become Editor of the Philosophical Transaction of the Royal Society. Perhaps inevitably, on receiving this second manuscript on turbulent flow from Reynolds, he sent it for review by Sir George Stokes. This time, however, the referee's response was very different. After a long period of silence, on October 31st 1894 Sir George, now equipped with a typewriter with both upper- and lower-case letters, sent his reply, a transcription of which appears in Figure 8 , effectively acknowledging that he didn't understand the work. The letter is a copy-book example of the 'on-the-one-hand…yet-on-the-other' style of review: Reynolds hadn't made his case – yet, he was an able man and the 1883 paper was sound; moreover the author had paid to have the present paper printed so obviously *he* thought it was important. However, the reviewer couldn't confirm that view … but neither would he assert that it was wrong!

Lensfield Cottage, Cambridge, 31 Oct.1894.

Dear Lord Rayleigh,
I must plead guilty to not having digested Professor Osborne Reynolds's paper, though much time has passed since it was referred to me.

I find it very difficult to make out what the author's notions are. As far as I can conjecture his meaning, I must say that I do not think that he has made out his point. He is however an able man, and in his former paper did very good work in showing that the condition of dynamic similarity which follow from the dimensions of the hydrodynamical equations when viscosity is taken into account are not confined to what I may call regular motions, but continue to apply (in relation to mean effects) even when the motion is of that irregular kind which constituted eddies, and which at first sight appears to defy mathematical treatment. The fact that the author has gone to the expense of printing the paper shows that he himself considers it as of much importance. I confess I am not prepared to endorse that opinion myself, but neither can I say that it may not be true.

I do not know if these remarks will be of any use in assisting the Council to come to a decision.

Yours very truly,
G.G. Stokes

Figure 8: Transcription of Sir G. Stokes' First review of the 1895 paper

Stokes' concluding sentence, Figure 8, seems to imply that he had finished with the matter but Lord Rayleigh evidently had other ideas. Although the exchanges are incomplete it seems that Rayleigh pressed Stokes to go further and, when Stokes pleaded that he had mislaid the copy of the paper, he arranged for him to be sent another copy. (Since the paper had been printed, Reynolds had evidently submitted several copies.) On December 5th Sir George sent this second copy back indicating that he had now found the copy originally sent to him. He added his regrets that he was '*not yet able to go beyond the rough indication contained in a letter sent to Lord Rayleigh some time ago.*' (Royal Society Archive Ref. 209 from Sir G. G. Stokes to Mr Rix.)

Meanwhile, Lord Rayleigh had sent the paper to a second referee, Horace Lamb, Professor of Mathematics at Manchester who a decade earlier had been elected a Fellow of the Society. One can only speculate why Rayleigh approached the only other senior fluid mechanicist in Manchester to review his own colleague's work. Nevertheless, on November 21st 1894 Lamb sent his longhand assessment which began with the brisk summarizing statement:

'*I think the paper should be published in the Transactions as containing the views of its author on a subject which he has to a great extent created, although much of it is obscure and there are some fundamental points which are not clearly established.*'

There followed three pages of detailed criticism including complaints at the inadequate definition of Reynolds' term '*mean-mean motion*' and a misprint in the manuscript (Royal Society Archive Ref. 208).

There are three further communications from the referees of which only one is dated. There is thus some doubt as to the actual sequencing though the most probable seems the following. At some point Sir George Stokes *does* send his review to Lord Rayleigh, a two-page typed assessment raising some of the problems with the paper he and, indeed, Lamb had aired earlier. Thereafter (or, possibly, even before that communication), the referees had made contact with one another, probably through the intervention of Lord Rayleigh, which led Lamb to prepare a joint report that Sir George attached to his letter of January 30th 1895 (Royal Society Archive Ref. 210):

'*Dear Lord Rayleigh,*

I enclose what Lamb meant for a draft of remarks to be submitted to the author. I think we are both disposed to say let the paper be printed, but first let some remarks be submitted to the author. There was very good work in the former paper, and there may be something of importance in this, but the paper is very obscure. In its present state it would hardly be understood.

Yours very truly,
G.G. Stokes'

This '*draft of remarks*' in Lamb's handwriting would not be legible in the present double-column format and is reproduced in typescript below:

"***Prof Reynolds' Paper***

The referees have found great difficulty in following the argument of this paper; partly in consequence of the fact that such terms as "mean-mean motion" and "relative mean motion" are used without any precise definition. There is a well-known distinction between molecular and molar motion; but it is not clear in the case of molar motion how any physical distinction is to be drawn between what is "mean" and what is "relative".

The introduction might be greatly shortened, as a good deal of it can only be understood after reading the rest of the paper. The purport of §5(a) p.3 is not evident. The author's view does not appear to be different from that generally held, but it is insisted upon as something new.

The statement, in §5(b), that the ordinary equations of a viscous fluid are true only when the motion is approximately steady, is questionable. It is perhaps based on the investigation on p.9; but this is purely mathematical; and there is besides a difficulty in seeing the connection between equations (7) and (8A). It would seem as if there had been a slip in writing $\underline{u}$ *for* $\underline{\bar{u}}$ *; but at any rate there is need of explanation. It is to be noted that the argument, if valid, would show that there are geometrical difficulties in the way of applying the idea of mean velocity to cases other than steady homogeneous motion.*

The essence of the paper lies in the equations on pp. 15, 16†*. If these are clearly established a great point would be secured, but its reasoning is somewhat obscure, and needs much amplification. The conception of 'mean-mean-motion' is a very delicate one and it is not made evident in what sense* $\bar{u}, \bar{v}, \bar{w}$ *are continuous functions, or on what conditions the derivatives* $d\bar{u}/dx$ *, etc. are supposed to be formed. The whole argument turns on questions of this kind, and it is just here that explanations are wanting.*"

†Author's footnote: Taking account of the 4-page insert made by Reynolds in the published version, the reference here is to Equations (13 – 19) in the published paper.

A margin instruction pencilled on the review in Rayleigh's hand, indicated that the report was to be copied (meaning that a clerk was to transcribe the review) presumably for onward transmission to Osborne Reynolds.

On receiving the referees' assessment, Reynolds evidently reflected on the criticisms and on February 19th sent the following reply:

"*Dear Lord Rayleigh,*

From the copy of the remarks on my paper on the criterion, which you sent me, it is clear that the referees have found great difficulty in understanding the drift of the main argument; namely that which relates to the geometrical separation of the components $\underline{u}$, $\underline{v}$, $\underline{w}$, *at each point of a system into mean-components* $\underline{\bar{u}}, \underline{\bar{v}}, \underline{\bar{w}}$ *and relative components* $\underline{u}', \underline{v}', \underline{w}'$ *and as to the conditions of distribution of* $\bar{u}$, $\bar{v}$, $\bar{w}$ *under which such separation is possible.*

I am very glad to know of these difficulties and of the opportunity it afforded me of improving the paper in this particular. As it is by such separation of the simultaneous component of velocity at each point, introduced into the equations of viscous fluid, that the evidence of a geometrical limit to the criterion appears independently of all physical considerations, any want of clearness on this point, no doubt, confuses the whole argument.

That I should have scamped the preliminary explanation of this part of the argument and diffused it over the whole paper I can only explain as a consequence of its definite character having blinded me to the difficulties which would thereby result in distinguishing what was new from what was already accepted, and of my desire to set forth the proof of the actual maintenance of the geometrical conditions under which such separation is possible afforded by experiment, as well as to indicate the general character of the *mechanical-actions, expressed in the equations of motion, on which such maintenance depends*".

This head-reeling sentence, 100 words in length, is also remarkable for its naturalness; its ready admission of the paper's weaknesses accompanied by its ready self-forgiveness. The letter then continues:

"*I now enclose you in M.S.S. a full preliminary description of this part of the argument which by permission I shall be glad to substitute for the first two lines of §5 p.3. It contains, what I hope will be found, a clear definition of the terms mean-mean motion and relative-mean motion as well as of mean-motion and heat-motions and of the geometrical distinctions between these motions. And although no physical-distinction between mean-molar and relative-molar is draw[n] other than what is implied by the geometrical distinction that the integrals of ρ$\bar{\underline{u}}$, etc, taken over the space determined by the scale or period-in-space of the relative mean motion ρ$\underline{u}$', etc, are the components of momentum of the molar motion of the mechanical system within S while the integrals of ρ$\underline{u}$, etc, taken over the same space are zero, it is shown that such physical distinction has no place in the argument any further than it is suppressed by the terms in the equations of motion.*"

The above passage, like preceding ones cited, bring out Reynolds' infatuation with long rambling sentences that stand starkly in contrast to Lamb's crisply stated criticisms. He finally acknowledges:

"*With reference to the difficulties in logic of §8 p.9, equations 7 and 8a, this is intirely removed by replacing the bar (*$\bar{\underline{u}}$*) which has dropped from the* $\underline{u}$ *in the left of equation 4, p8.*

There are, I am sorry to say, certain other misprints in the paper which must have increased the inherent difficulties of the subject.

Very truly yours,
Osborne Reynolds"

Apparently, no further exchanges between author and editor remain in existence and, since there is no copy of the original manuscript, it is not certain how extensive were the changes actually made. One clear indication of a change in the published version of the paper is that four pages of §5 of the Introduction are placed, entirely without explanation, within square parentheses and end with the date: Feb 18, 1895 (that is, the day preceding Reynolds' sending his response). Thus, this passage clearly seems to be what Reynolds referred in his reply to Rayleigh as '*the full preliminary description of this part of the argument which by permission I shall be glad to substitute for the first two lines of §5. p.3.*' Since this was the only significant change referred to by Reynolds it appears likely that all other changes were minor, mainly consisting of corrections to typographical errors in the original.

Despite its rather luke-warm reception by the two eminent referees, the paper is seen today as a mighty beacon in the literature of Fluid Mechanics. First and foremost was the decomposition of the flow into mean and fluctuating parts leading to the averaged momentum equations (now known as the *Reynolds equations*) in which the *Reynolds stresses* appear as unknowns. In fact, throughout the analysis Reynolds treated the averaging in a form akin to what is now known as mass-weighted averaging, sixty years earlier than the source that is usually quoted for introducing that strategy. It was surely just that his experiments had used water as the fluid medium that led to this feature being ignored. The paper's other major analytical result was the turbulent kinetic energy equation on which he observed that the terms comprising products of Reynolds stress and mean velocity gradient represented a transfer of kinetic energy from the mean flow to turbulence. As an indicator of just how far this discovery was ahead of its time, we note that the corresponding, albeit simpler, equation for the mean square temperature fluctuations was not published until the 1950's, Corrsin [13].

Reynolds' purpose in examining the turbulent kinetic energy equation was to provide an explanation of why the changeover from laminar to turbulent motion should occur at a particular value of the Reynolds number. Indeed, that was the driving rationale for the whole paper. He considered fully-developed laminar flow between parallel planes on which a small analytical disturbance was superimposed which permitted him to obtain expressions for the turbulence energy generation and viscous dissipation rates integrated over the channel. The relative magnitude of these two processes varied with Reynolds number and the lower critical Reynolds number he identified as being that where the overall turbulence energy generation rate had grown to balance the viscous dissipation rate. That his estimates were inaccurate is now seen as irrelevant since the paper contained more than enough novelty for the world of Fluid Mechanics to absorb over the ensuing decades.

3. END PIECE

Publication of the second of his major works on turbulent flow did not mark the end of Reynolds' creative outpourings. As noted, the highly influential paper on film-lubrication [10] appeared in the following year and in 1897 he gave the Bakerian Lecture to the Royal Society [15] reporting measurements on the mechanical equivalent of heat. Of this latter, huge experimental programme, in which he obtained the equivalence within 0.2% of modern determinations, Gibson [2] has written "*This whole investigation is a model of* *scientific method and may claim to rank among the classical determination of physical constants*."

His final years in Manchester were marked by his intense efforts to provide a mechanical theory of matter and the ether which culminated in his work *The sub-Mechanics of the Universe* being reported orally at the Royal Society in 1902 and published as Volume 3 of his collected works [16]. As Lamb's [1]obituary notes, however, in what must be seen as a kind understatement, "*unfortunately illness had begun gravely to impair his powers of expression and the memoir as it stands is affected with omissions and discontinuities which make it unusually difficult to follow*". Gibson [2] has noted that 1903 was the last year in which Reynolds was able to take an active role in the department, his declining mental state (a condition that today might have been diagnosed as Alzheimer's) leading to his retirement from the University at the age of 63 in 1905.

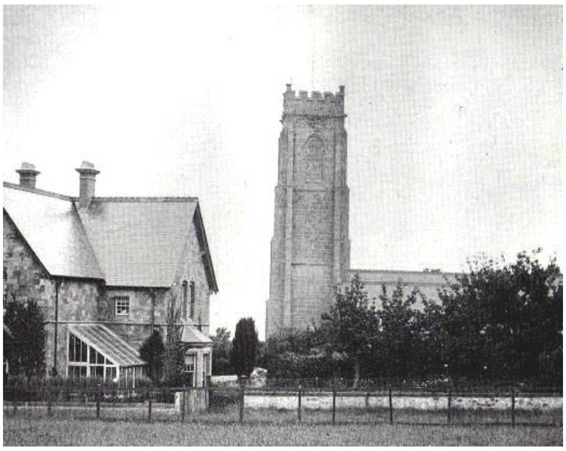


Figure 9: St Decuman's vicarage c.1900 where Reynolds spent his final years (from Wedlake [17]).

Thereafter, the family left Manchester to live at the vicarage in St Decuman's, a hamlet on the hill above Watchet, a small though not insignificant historical port in north-west Somerset. The church and the vicarage are shown in Fig.9 in a photograph from c.1900. Why Reynolds or, perhaps more accurately, given the prevailing circumstances, his wife should have chosen Watchet as their retirement base is unknown though the fact that both their fathers had been clergymen probably provided the essential contacts for them to have been able to rent the vicarage. And there they remained until his death on February 21st, 1912. The 1911 census discloses that the return for the Reynolds household was completed by Annie on behalf of Osborne and that, numbered among the residents, in addition to their daughter, Margaret Charlotte, and two domestic staff, was a live-in sick nurse. Evidently, his final years were difficult ones both for him and his family.

His funeral in St Decuman's church was attended by Horace Lamb (Cameron [14], citing The West Somerset Free Press) and he is buried in the churchyard, his gravestone being an elegant *art nouveau* cross with his name and the dates of his arrival and departure beautifully engraved thereon, Fig. 10. His wife who lived until 1942 is interred with him while two grandsons, (sons of Henry Osborne Reynolds) both of whom were killed in action in the Second World War, are also memorialised on the gravestone.

Figure 10: Osborne Reynolds' gravestone in St Decuman's churchyard.

In closing, it is appropriate to ask why it was that, in his lifetime, Osborne Reynolds was never awarded any national honour. The obituary notice that appeared in *Nature* just a week after his death, began: "*In Professor Osborne Reynolds……Great Britain has lost its most distinguished scientific engineer*." Towards the end of the piece, after noting his admission to the Royal Society, the award of the Society's Royal Medal and his honorary doctorate from Glasgow University, it concluded by remarking that that "*was the only public recognition he ever received*". The tone and positioning of this last observation clearly leave the impression that the writer at least felt there was a measure of injustice in Reynolds not receiving other public honours: why it was that he did not end his days as *Sir* Osborne Reynolds (as, in fact, a few of the web entries about him do, erroneously, refer to him). Indeed, one may remark that among leading fluid mechanicists, George Stokes was knighted as were later Horace Lamb and Geoffrey Taylor while William Thomson was, as noted above, first knighted and later admitted to the peerage as Lord Kelvin of Largs. If we exclude the last named who made notable contributions in several other walks of life, none of those cited contributed as much to the advancement of fluid mechanics and thermo-dynamics in all its varied aspects as Osborne Reynolds (not just his very particular studies of turbulent flow on which the present article has focused).

A possible reason could be that he *was* offered such an honour and declined it. This seems highly unlikely, however, first because, while he would have been at pains to dissociate himself from the formal trappings and snobbery of such a title, he would have been delighted if somewhat bemused by the award. Secondly, if such an offer had been made and declined, this fact (while kept secret during his lifetime) would surely have been disclosed following his death in one or more of the several obituaries written by his colleagues.

Thus, there remains the question of why he was not so honoured. The writer suggests three reasons which collectively conspired against him. First, it would seem that in his public demeanour he lacked sufficient *gravitas* to mark himself out as a sound leader of men on high scientific matters. There are numerous anecdotes of him setting puzzles for his audience. In contrast, both George Stokes and Lord Kelvin had served as President of the Royal Society and their advancement was assured. G. I. Taylor came to prominence a half-century after Reynolds and undertook research in both world wars on behalf of the war effort, including being part of the British delegation working on the Manhattan Project. His case is thus very different from Reynolds'. Finally, Lamb, the only other Mancunian from the group, served twice as Vice-President of the Royal Society and as president of the London Mathematical Society. His ability to cut through tricky problems – which must have served him very well throughout his career - is well illustrated by his review of Reynolds' 1895 paper cited earlier. Moreover, Lamb also possessed the second of the qualities that Reynolds unfortunately lacked: longevity! He was knighted only in 1931 at the age of 82.

The final reason offered as contributing to Osborne Reynolds being overlooked for national honours is that the importance of his works was often not recognized until long after their publication. As his obituary in *Nature* observed: "*Well in advance of his time, in many cases year elapsed before the practical bearing of his researches was fully appreciated; even now the sphere of his influence on engineering progress is still widening*." We may note, wryly, the correctness of this assertion, since the obituary in *Nature*, while summarizing many of Reynolds' important research contributions, made no reference at all to the turbulent flow papers central to the present appreciation. We should be indulgent of that lapse, however, for, when, in 1895, his strategy for the analysis of turbulent flows was published in *Phil. Trans Roy Soc*, could anyone, even the author, have foreseen that it was destined to shape the direction of research in engineering fluid mechanics for the next century?

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