Fluid dynamics knowledge base

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Abstract

Computational fluid dynamic simulations reveal deficiencies in the fluid dynamics knowledge base. The Colebrook-White equation and Moody chart for fluid friction are of particular concern. A due diligence study finds they are based on fabricated data and flawed reasoning. New fluid dynamics research domains emerged in the past 100 years. Researchers moved into new domains, but procedures did not exist to verify and make available validated data from abandoned domains.

A fluid dynamics knowledge base and AI inductive learning and monitoring resources are required to support professionals, lecturers, and STEM students. Benefits from the resources include:

- Open access to a validated fluid dynamics knowledge base
- Reduced risks of fluid system failures that result in deaths and injuries, environmental damage and billions of dollars in yearly losses
- Potential for saving over a trillion US dollars to reach net zero CO_2 emissions by 2050
- Engendering STEM students to understand fluid flow behaviour better and construct science based conceptual models
- Justifying the research facilities need to determine fluid dynamic parameters to internationally agreed levels of precision.

Part 1 provides evidence to justify fluid dynamic resources. The forms of these resources are suggested in Part 2.

Keywords: Flawed Moody chart, fluid dynamics knowledge base, visualising fluid flow behaviour, AI adaptive learning software, energy savings, due diligence.

Part 1. Need for multimedia fluid mechanics resources

1. Introduction

Researchers find flawed data when validating computational fluid dynamic (CFD) predictions against experimental data. What is particularly disturbing is that data used to design state-of-the-art products and processes are flawed. The calculations affected are for fluid systems that consume over 35% of global electricity, equivalent to the combined annual electricity consumption of China, India and Japan (Section 5). Savings of over 5% of global electrical energy are possible using existing fluid dynamics knowledge and data.

A due diligence study provides the evidence to support fluid dynamics researchers in their quest to replace the flawed Moody friction factor chart. The need for due diligence is a key theme of this paper. Practising due diligence leads the author to comment on the contentious subject of data used in recent boundary layer research projects. A due diligence study indicates that many researchers have used unsound experimental data. Numerous conflicting values for fluid dynamic parameters are promoted, with persistent disagreement among researchers. Parameters are used in state-of-the-art supercomputer software for weather forecasting (1) and numerous other challenging simulations. Direct numerical simulation (DNS) of semi-organised very large scale motions (VLSM) in wall-bounded turbulent flows has revealed their importance. Studying these motions provides insights into reasons for parameter disagreements. However, the capabilities of experimental facilities available to researchers cannot reveal subtle variations in flow phenomena to indisputable accuracy. International collaboration led to agreements on fluid dynamic parameters for flow metering. National flow metering laboratories and groupings of stakeholders support flow metering parameters that allow the equitable trade of trillions of dollars of fluid products per year. Fluid dynamic parameters are used in millions of CFD simulations. Their value to society is probably comparable to that of flow metering parameters. Infrastructure is required to determine their value appropriate to their importance.

A report Commissioned by the UN High-Level Climate Action Champions estimates that an investment of 125 trillion US dollars is needed to meet net zero CO_2 emissions by 2050 (2). Decarbonising industry, transport, commerce, capturing and storing greenhouse gases, and generating electricity depends on fluid systems. Allowing for the time to develop a fluid dynamics knowledgebase and the tools to exploit the base and for fluid system aware STEM graduates to disperse into the workplace, benefits from a fluid dynamic database and the tools to exploit the database equivalent to over a trillion US dollars could potentially be achieved by 2050.

Forty years ago, in a handbook (3), the author collected internal flow data from research teams worldwide and combined them with data from research programmes at the British Hydromechanics Research Association (BHRA). Researchers at BHRA validated extensive data from other laboratories. Aware there was no mechanism to spread the data globally, it was reasoned that investors seeking to recover their investment would be the most effective way to reach a global audience. BHRA secured venture capital to develop one-dimensional (1D) CFD software with data from the handbook at its core. BHRA staff involved with the research joined the commercial exploitation organisation and were instrumental in developing the software's multi-physics and transient capabilities. Versions of the software are today integrated with 3D CFD and life cycle management software (4). The software has been adopted by aerospace, automobile and other companies that produce multiple versions of products. Fluid dynamic specialists in these companies design fluid systems, and their testing of fluid systems is rigorous. This has allowed companies to gain confidence in the handbook's data, and it has become the de facto standard for fluid system simulation in these industries. However, unnecessary energy is mainly consumed by industries that operate large one-off process and power generation plants and commercial buildings. One-offs will likely be designed by non-fluid dynamic specialists or designers who aim to minimise first-time costs while meeting performance guarantees for a process for which fluid systems are auxiliaries. With uncertainty over fluid dynamic data, the natural action is to oversize auxiliary systems.

Auxiliary fluid systems in process and power plants can consume MWs of unnecessary electricity.

This paper is essentially a plea for fluid dynamics to gain a discipline home in which scientific, academic, industrial and environmental stakeholders own a fluid dynamics knowledge base and tools to exploit the base. The author has aimed to bring together sufficient information in this paper to provide a resource from which Science Institutions and others can justify to governments and research funders that a fluid dynamics discipline home would substantially benefit society. This does, however, mean this paper is extensive. Technical detail is mainly confined to the Appendices.

Providing evidence to justify a discipline home has taken the author into STEM education areas characterised by an almost overwhelming surfeit of publications to convince academia to adopt research-based teaching approaches. As pointed out in the literature, papers can be unread by their target audience. The educational references in this paper are examples that the author considers insightful in creating a case for developing a fluid dynamics knowledge base. Figures in the text are limited to those required in a due diligence study to illustrate the fabrication of experimental results. The figures related to due diligence on other flawed experiments can be found in the relevant reference.

Fluids in motion are essential to many areas of science, the built and the natural environment, and are fundamental to life. Scientific disciplines and industrial sectors have assumed responsibility for aspects of fluid dynamics of importance to them. This has led to the fragmentation of the fluid dynamics knowledge base. Areas that are not seen as academically challenging have stagnated. These academically neglected areas contribute significantly to excess energy use and CO_2 emissions. Turbulent boundary layers are an active area of research with hundreds of academic research groups. Justification for funding mainly relies on the potential for energy savings. It can be shown that advances in understanding turbulent boundary layers have many benefits. Contrary to persistent claims, benefits do not include substantially reducing energy consumption to meet net zero greenhouse gas emissions by 2050 (Section 10). Information is provided where investment is required to reduce greenhouse gas emissions.

1.1 Historical developments in fluid system simulation

Engineers in the 19th century built piping systems to supply clean water and remove sewage. These systems were human history's most important health event and made modern cities possible. Without a significant fluid dynamics science base, engineers devised nonhomogeneous equations, monographs and tables to conduct fluid system calculations. As oil and gas, heating and ventilation, and other industries developed, they devised friction equations and calculation methods specific to their industry. These non-scientific prediction methods are included in fluid mechanics textbooks, design manuals and computer programs. Their range of applicability is not well documented, and some are being applied outside their range.

In the nineteen-thirties, fluid dynamicists began to build a firm science base for internal flow system simulation, but their work was interrupted by World War 2. After the war, internal flow systems were not a research priority. Piping and duct systems grew in size to the extent that component pressure losses depended on Reynolds numbers. System complexity increased, and so-called component "minor losses" became the major losses in numerous systems. Over-prediction of pressure losses resulted and continues to result in the oversizing of fluid machines (Section 4). The Reynolds number dependency of component loss coefficients is not acknowledged in student textbooks, design manuals and computer programs. Between 1950 and 1980, research groups greatly extended parts of the database, but their contributions are not widely known or included in design manuals and textbooks.

A recent study on the importance of fluid dynamics to the UK economy (5) found that "Fluid dynamics generate £13.9 billion worth of output from over 2,200 firms and employs 45,000 people. The total UK turnover of firms engaged in fluid dynamics exceeds £200 billion and together they employ over 500,000 people, illustrating how fluid dynamics activity is often embedded in larger organisations." Globally companies' turnover in embedded fluid dynamics activities is trillions of dollars per year. Much of this embedded fluid dynamics activity is carried out by scientists and engineers who are not fluid dynamics specialists. This highlights the importance of effective fluid dynamics teaching in STEM curricula (Part 2).

Every year events in fluid systems cause pressure containments to fail. Failures result in deaths, injuries, environmental damage, and billions of dollars of yearly losses (Appendix A). Fluid system accidents usually involve causes that investigators find organisation boards and management should have addressed. However, had scientists and engineers better understood fluid flow behaviour in the years preceding the design of a failed fluid system, then events leading to accidents may have been avoided. Empowered with solid background knowledge in fluid dynamics and the ability to conceptualise relevant phenomena, individuals can act to reduce or eliminate conditions that lead to breaches of fluid system containments. Many fluid system accidents evolved over a significant timescale. If operators and their supervisors had better understood fluid flow behaviour, they could have avoided or mitigated the consequences of unfolding events in the time available.

Fluid system designers, operators and managers need to see in their mind's eye flow behaviour within fluid systems, including the effects of control and monitoring systems under steady-state and upset conditions. Fluid dynamic researchers rely on advanced computer visualisation of physical and computational experiments to understand complex flow behaviour. They use visual presentations to communicate with colleagues and other researchers and to prepare scholarly papers. However, in their lecturer's role, they generally do not emphasise visualisation in the mind's eye. They generally teach fluid mechanics as an equation-based subject (Part 2).

The 2020 Annual Review of Fluid Mechanics includes a paper, "Machine Learning for Fluid Mechanics" (6), with the following observation "Indeed, physics-based engineering of fluid systems is a highwater mark of human achievement. However, there are serious challenges associated with equation-based analysis of fluids, including high dimensionality and nonlinearity, which defy closed-form solutions and limit real-time optimisation and control efforts. At the beginning of a new millennium, with increasingly powerful tools in machine learning and data-driven optimisation, we are again learning how to learn from experience."

An essential part of experience-based learning is resolving conflicts between contradictory ideas and data. The field of fluid dynamics is full of contradictory ideas and data that practitioners claim support particular turbulence models. Research funding has been directed toward understanding turbulence for over a hundred years. There has been little funding or academic merit in conducting due diligence on past experimental studies, though these studies support current research activities. This situation is changing because of the need to validate CFD studies. Direct numerical simulation (DNS) of some mean flow variables, such as pipe friction, is now possible (Section 5.2). Recent DNS studies of how friction factors vary between smooth and fluid dynamically rough flow conditions (7) have confirmed a review of the knowledge regarding wall-bounded turbulent flows (8) that the Moody friction factor diagram is erroneous. The Review (8), by six international turbulent flow researchers, recommended that the Moody diagram "be phased out".

The recommendation in The Review (8) that the Moody diagram should be phased out was not based on a due diligence study of the data sources used to generate the diagram. It was based on evidence accumulated over tens of years that the diagram does not represent reality. A due diligence study of the experimental work behind the diagram finds in Appendix B:

- Experimental work was seriously flawed
- Fabricated data
- Erroneous observations and conclusions.

2 **The need to practice due diligence**.

The Moody friction diagram (9)is the most famous and useful fluid mechanics diagram. Globally, millions of engineers and scientists use it. The most famous fluid dynamics model is Prandtl's boundary layer model. Models are vital, but a model's limitations are discovered as technologies advance. A more accurate model is sought, but the limitations of the existing models are not necessarily communicated to those who need to consider the model's limitations. In the case of Prandtl's boundary layer model, 80 years after one limitation was demonstrated, this limitation is yet to be included in fluid mechanics textbooks.

An early example of boundary layers for which Prandtl's boundary layer model should be reformed and the Colebrook-White equation on which the Moody diagram is based are linked through C M White of Imperial College and the Royal Society. It is appropriate to discuss this link to show that learning fluid mechanics through experience needs to be within a due diligence environment.

A paper by White, "The equilibrium of grains on the bed of a stream", was published in the Proceedings of the Society in 1940 (10). It described remarkable ingenuity in measuring shear stresses of water flow over a bed of granular material. White acknowledges the limitations of his experiments, but his approach's meticulousness meant that his observations were valid. From particle movements and measurements with turbulent flow, he observed that:

- Areas of a loose flatbed of granular material are set in motion well before the mean shear stress is sufficient to move a bed generally
- Local fluctuations cause the shear stress at a bed’s surface to vary and reach a maximum of about twice the mean.

White attributed what he observed to turbulence outside the viscous layer penetrating to the bed. These fluctuations are now associated with turbulent burst and sweep events that eject low-energy fluid from the wall and bring high-energy fluid to the wall (8) and the passage of very large scale motions (VLSM) above a bed (11). The importance of burst and sweep events on phenomena such as flow-accelerated heat transfer, corrosion and thermally induced fatigue cracking is not included in textbooks.

In contrast to White's exemplary experimental work, Colebrook and White's "Experiments with fluid friction in roughened pipes", published in the Society Proceedings in 1937 (12), contains experimental errors, unwarranted assumptions, and fabricated data (Appendix B). Colebrook used the paper's results in "Turbulent flow in pipes with particular reference to the transition region between the smooth and rough pipe laws ", published in 1939 by the Institute of Civil Engineers (13). This paper contains the Colebrook-White equation, in which Colebrook claimed better-represented friction factors in the region between smooth pipe flow and fully turbulent flow than those measured experimentally by Nikuradse (14) (Appendix B.2). When correctly interpreted, the measurements in the Colebrook-White paper support Nikuradse's work.

From the writing style of the 1939 paper, it can be concluded that Colebrook was responsible for the 1937 paper in Proceedings of the Society. Colebrook misled White, G I Taylor, who communicated the paper to the Society, Hunter Rouse (15), Moody (9), who justified the Moody diagram based on Rouse's judgement of the validity of the Colebrook White equation, and numerous researchers over the past 80 years. His deceit has caused incalculable damage scientifically and delayed the understanding of events in the transition region between fluid dynamically smooth and rough wall flow. Due process can correct the research record but not the numerous thesis and papers that have relied to some extent on Colebrook's work. Researchers have added to misconceptions about the transition region by making incorrect assumptions about Nikuradse's pipe roughness (Appendix B.2.)

The author is one of many who have recommended using the Moody diagram for engineering calculations (3). To reduce computing time, the author recommend using an explicit friction factor equation (16) instead of the implicit Colebrook-White equation. As this paper shows, the author, 50 years ago, failed to carry out due diligence on Colebrook’s work. Had the author done so, it is likely, many researchers would not have used Colebrook’s work. The author's failure may at least cause some future researchers to conduct due diligence on the references they quote, which are directly relevant to their research.

2.1 Fluid system data that can be validated

A fluid system coefficient replicated many times is the friction factor in fluid dynamically smooth pipes at Reynolds numbers up to 10^6. Above Reynolds numbers of 10^6 recent measurements have produced contradictory friction factors. These contradictory results affect current boundary layer research projects. Therefore, understanding the reasons for these differences is essential (Appendix D).

Following a well-designed inlet, a virtually constant static pressure gradient is established along a smooth pipe in a relatively short distance (20 to 30 pipe diameters). The mean velocity profile and turbulence properties, including very large scale motions (VLSM), continue to evolve over a distance five or more times greater (17). In the first 15 diameters or so of pipe after a smooth contraction, the static pressure gradient is noticeably steeper than further downstream because the mean kinetic energy of a developing velocity profile increases by approximately ten per cent. This energy is not recoverable and is debited to the inlet. By debiting components with head loss over and above steady-state friction in their downstream pipe or passageway, the total energy loss can be accurately tracked through a system using a 1D CFD approach. A system is represented by nodes (components) connected by pipes or passageways for steady-state computer simulations. For transient analysis, pipe and component lengths are considered.

Flow disturbances from many components can be detected in the mean velocity profile for more than a hundred diameters downstream. However, an essentially developed friction gradient is usually established within 30 hydraulic diameters, even after severe flow disruptions. Measuring validatable component loss coefficients requires accurate measurement of the steady-state friction gradients before and downstream of a component. The difference between the inlet and outlet steady-state friction gradients is used to calculate a component's loss coefficient. The importance of using friction gradients is that if the measured friction gradients do not agree with the friction gradients for the pipe or duct measured without the component, an error in the measurements or the flow behaviour needs to be investigated.

The majority of loss coefficient studies measured the static pressure at a location upstream of a component and a location downstream. The static pressure difference minus an assumed friction loss in the pipe sections between the measuring locations was used to calculate the loss coefficient. This method is not self-checking and invariably involves downstream static pressure measurements too close to a component to record all losses. In addition, loss coefficients depend on the assumed pipe friction factor and static pressure tapings at just two locations. The difficulty in making and maintaining fault-free static pressure tapings in pipes and ducts is discussed in Appendix C.2.

3. BHRA Loss coefficient studies and recent studies

The author was a team member at the British Hydromechanics Research Association (BHRA), who, over 15 years, carried out experiments to determine the loss coefficients for fluid system components. Prior studies had shown savings of MWs of power by improving the design of cooling water systems for gigawatt power stations. Studies ended investigated pressure losses in pipework within compressor yards of the North American gas distribution network. By the 1980s, fuel costs to power the network had reached a billion dollars annually. In some compressor yards, flow through interacting T-junctions and bends dissipated up to ten per cent of the compression energy input.

BHRA researchers were involved in investigating numerous fluid mechanics problems. One example was a process plant with a cooling water installation with 50 MW pumping power when 30 MW would have been adequate. The excessive pumping capacity caused numerous problems, including velocities in heat exchanger tubes exceeding the critical erosion/corrosion velocity. Seawater contaminated the process fluid. It is believed that the cooling water system design was based on a design guide (18) that contained coefficients from 1930s tests on rough surface components. Consequently., coefficients were independent of the Reynolds number and substantially higher than those for modern components. Today's fluid mechanic textbooks, design handbooks, and computer programs contain similar 1930s loss coefficients.

The BHRA investigators experimentally validated many loss coefficients from the literature. An observation from the validation studies was that nearly all reproducible loss coefficients were generated by research teams that had been active for more than five years. Research teams accumulated expertise in building facilities to measure valid coefficients. It was evident that researchers had to acquire the ability to see in their "mind's eye" fluid flow behaviour. A classic example of understanding fluid flow behaviour is Kline's research group at Stanford University, the leading diffuser research group in the 1950s and 60s. Diffuser performance depends on boundary layer conditions at entry. Extensive flow visualisation experiments on boundary layer flow contributed to Kline's group's seminal paper on coherent turbulent flow structures (19). Numerous research groups worldwide now study these structures.

During the BHRA studies, over a thousand papers on experiments measuring loss coefficients were assessed to determine whether they contained valid data. Less than ten per cent of experimental studies were considered to have been set up in such a manner as to measure validatable loss coefficients. What was particularly disturbing was the researcher’s cursory review of the literature. Loss coefficients found in handbooks were quoted without returning to the original experimental work. Experimental studies were justified by disagreements between loss coefficients from inappropriate sources. A notable absence from studies was evidence that researchers understood flow behaviour, and comments in some papers indicated that researchers misunderstood flow behaviour.

3.1 Recent fluid systems studies

Since the BHRA studies, substantial projects to measure fluid dynamic coefficients have been reported in the literature. Due diligence studies on the projects in Appendix C show that:

- A collaborative European Commission funded project to improve the design of ventilation systems adopted a non-scientific method of measuring loss coefficients

- A project that reached the highest Reynolds number ($>10^7$) for bend loss coefficient studies did not understand fluid flow behaviour and recorded loss coefficients in error by a factor of two
- One project concluded that coefficients depend on duct size and Reynolds number. This erroneous conclusion is being propagated in ventilation system design guides
- Extensive studies on commercial pipe fittings for water systems reported loss coefficients inconsistent with known validatable coefficients

A study of friction factors in steel pipe incorrectly concluded that friction factors did not follow the expected trends in the transition from smooth to fully rough flow.

Boundary layer studies require accurate wall stress measurements. Friction factors measured in pipes are converted to wall shear stress. Disagreements over smooth wall friction coefficients have arisen in recently commissioned pipe bases research facilities that can reach Reynolds numbers up to $3x10^7$. A due diligence study of possible reasons for the disagreement is provided in Appendix D.

4. Operating fluid systems studies

"Over 35% of global electricity is consumed by pumps, fans and compressors, equivalent to the combined annual electricity consumption of China, India and Japan. This is likely to double by 2040 according to the International Energy Agency." (20).

Studies on operating fluid systems have been conducted in several countries to determine how efficiently they use energy. Researchers involved with studies on pumped systems in the USA commented that "anecdotal evidence indicates that about 75% of all pump installations are oversized" (21). A similar oversizing of fans occurs. Oversized machines consume unnecessary energy, and the operating points are away from the design points. Operating away from a design point causes the flow conditions within a machine to deteriorate, thereby increasing the dynamic forces on bearings and seals. The result is higher maintenance costs and a reduced time to machine failure.

US fluid system studies have resulted in guides on upgrading existing pump and fan-powered systems (22, 23). Targeting existing piping systems is logical because piping systems in the process, power, oil and gas, and many other industries operate for over 30 years. There are 20 times more pumps in operation than those sold annually (24). For the reasons discussed in Section 11, actions to reduce unnecessary energy use in large industrial fluid systems have made limited progress.

5. The Moody diagram and its replacement

5.1 Birth of the Moody diagram

Rouse (25) provides an account of his part in the birth of the Moody diagram. In 1942, he used the Colebrook-White equation and other friction data from the literature to develop a diagram with coordinates unsuitable for general engineering use. Moody advised him to change the diagram to one using conventional coordinates, but he declined. Moody subsequently produced his diagram.

In his 1942 paper, Rouse used friction factor data from Freeman's 1892 experimental work (26) to compare with the Colebrook-White equation predictions (Colebrook also used some of Freeman's friction data). Although the agreement with the Colebrook-White equation was not good, it was adequate for Rouse to describe the Colebrook-White equation as "a close approximation to the actual resistance law". In the forward to his paper, Moody (9) acknowledged Rouse's contribution and commented, "The author does not claim to offer anything particularly new or original, his aim merely being to embody the now accepted conclusions in convenient form for engineering use". Moody referenced Colebrook's paper but not the Colebrook White paper.

The only photographs of pipe surfaces in Freeman's reports are of new wrought iron pipes with simulated tubercules. The poor pipe surfaces, by today's standards, are apparent from the photographs. Pipes had granulated surfaces (Freeman's description) with numerous faults and protrusions visible in the photographs. The ColebrookWhite pipes had surface roughness characteristics more analogous to Nikuradse's than Freeman's wrought and cast iron pipes.

5.2 Replacing Nikuradse sand roughness

In a paper Moving beyond Moody(27), Flack provides insightful comments on characterising surfaces involving Nikuradse's roughness and the potential for direct numerical solution (DNS) to determine the drag coefficients of generic rough surfaces. She referred to studies (7) that used DNS to simulate frictional drag on surrogate Nikuradse sand roughened surfaces. The DNS studies agreed with Nikuradse's experimental transitional curves between fluid dynamically smooth and rough surfaces.

Surrogate Nikuradse surfaces were generated by scanning grit-blasted surfaces and electronically processing a scan to obtain smoothly varying periodic topologies in the streamwise and spanwise directions. The aim was to achieve surfaces that generated the same transitional friction factor curve shapes as Nikuradse’s between hydrodynamically smooth and rough surfaces. Appendix B.2 points out that the form of Nikuradse's roughness has generally been misunderstood.

Surface roughness has a myriad of forms and spatial distributions. Based on the available evidence, it would seem sensible for the turbulence research community to make a clean break from the past and agree on a library of electronically stored comparator surfaces representing a broad spectrum of pipe and other surfaces encountered in industry and commerce. With an agreed set of comparator surface topologies, turbulence research groups could better cooperate to understand turbulent flows over rough surfaces and the events that result in inflectional transition friction factor curves.

Substantial literature exists about surface forms that do not produce inflectional transition curves. Many characteristics of such surfaces, two-dimensional features, ribs, and corrugations, are known. Therefore, it is practical to build a library of surfaces that do not have inflectional transition curves.

5.3 Replacement friction diagram and equation

An authoritative group of practitioners need to endorse a new friction factor diagram. An endorsement would aid in phasing out the Moody diagram and dimensionally nonhomogeneous friction equations. One of these equations widely used in the water industry is the Hazen-Williams equation. For large water transmission systems, the Hazen-Williams equation is used outside its range of applicability (28, 29). There are uncertainties regarding the capacity of large systems designed using the Hazen-Williams equation.

Equations linked to the replacement diagram also require authoritative backing to discourage the proliferation of friction factor equations, as has occurred for the Colebrook White equation. The proliferation of equations has led to papers assessing the "accuracy" of over 25 equations (30, 31), all developed without first checking the validity of the Colebrook-White equation, demonstrating the need for authors to confirm they have practised due diligence.

5.4 Laminar and laminar to turbulent flow friction factors

Applications involving laminar flow are increasing with the development of:

- Lab-on-a-chip devices for medical and other diagnostic applications
- Miniature heat exchangers for electronic cooling
- Miniature chemical and biological reactors.

Manufacturing methods for devices with small bores and microchannels may generate surface roughness that affects laminar flow friction factors. Arguments exist for and against laminar roughness effects (32, 33). Nikuradse's data (14) indicated that laminar friction factors were unaffected by roughness. However, the validity of Nikuradse's laminar and laminar factors is questionable. Many of his head differential readings in the transition and laminar region would have been less than a millimetre of water gauge. Substantial data scatter would have occurred but was, presumably, eliminated by Nikuradse's practice of rejecting data points that did not meet his expectations (34).

Conducting experiments on flows through microtubes and passages is challenging, as pressure and temperature differences can affect fluid properties requiring compressible flow calculations. It is still a work in progress to generate, bring together and plot friction factors in the laminar and laminar to the turbulent transition region.

6. Conclusions on Part 1

Numerous fluid dynamics research opportunities have emerged over the past 100 years. Research groups built expertise in particular domains but needed to move on to in-vogue and funded domains. Mechanisms did not exist to verify and codify data and knowledge before the research domains were abandoned. Consequently:

- Society has born increased costs of products and services while suffering from unnecessary pollution and greenhouse gas emissions
- Industry and commerce have been using unnecessary energy to power fluid machines

- Accidents involving the loss of life, environmental damage and substantial cost may have been avoided.
- Experimenters entering abandoned domains lacked guidance on the variables to control and how to set up experiments to generate valid data
- Lecturers have not had access to up-to-date teaching materials
- Generations of STEM students have graduated without appropriate knowledge about fluid systems.

Part 2 Fluid dynamics knowledge base and STEM Learning

7. Introductory fluid dynamics

Our relationship with fluid dynamics is very different from that of other physics subjects. We are born into, breathe, and exist in an ocean of air and depend on the movement of water, and water-based fluid flows in our bodies and surroundings. Our lives involve dynamic interactions with fluids. From childhood, the human mind creates models of fluids in motion to make sense of how the world works, but conclusions about the causes and effects of fluid motions can be counterintuitive. Students arrive at university with mental models of fluid flow behaviour that do not match scientific models. Extensive research has highlighted the difficulty of replacing non-scientific mental models with scientific ones (35,36).

A mental capability that STEM students need is good spatial abilities. "Recent analyses have shown that spatial abilities uniquely predict STEM achievement and attainment" (37). Good spatial ability is essential for an understanding of fluids in motion. Pre-university education prioritises quantitative and verbal abilities over spatial abilities (38). Studies have reported the effective development of spatial abilities integrated into preliminary physics courses (39). Good spatial abilities are essential to deep learning concepts to solve fluid dynamics problems (40).

If flawed models of fluid flow behaviour are not replaced by scientific models and adequate spatial visualisation capabilities are acquired, a student may adopt memorising rote learning. Fluid dynamic rote learners can achieve passing grades. However, rote learners graduate without a rich store of fluid dynamics knowledge from which they can reason and build mental models of fluids in motion for new situations. Other students effectively accept that they do not understand at a fundamental level, which is one of the reasons fluid mechanics has a reputation among students "as mathematically onerous, conceptually difficult, and aesthetically uninteresting; anecdotally, undergraduates may choose to opt-out of fluids engineering-related careers based on their early experiences in fluids courses" (41).

In an ideal world, introductory fluid mechanics course lecturers should establish individual students' knowledge state and spatial abilities and devise a learning strategy for each student. However, this is not feasible. An approach to the ideal is becoming practical:

- AI-based learning and assessment tools that enable students to monitor their learning mastery and allow instructors to monitor individual students’ performance
- Promoting conceptual understanding of flow behaviour through visualisation

- Research-based teaching and learning practices

Abundant studies on STEM learning success emphasise the importance of introductory physics courses. However, introductory courses are often accorded a low priority. A comment in a report of the National Advisory Group of Sigma Xi (42), "The reliance of many research-orientated universities on teaching assistants who lack the motivation, preparation, and (especially in the case of some foreign students) the communication skills to teach well strikes another blow at the quality of undergraduate instruction." This comment reinforces conclusions from numerous studies that introductory physics courses need to be taught by inspirational lecturers in a department where the faculty have adopted research based teaching methods and appropriate course content. In the case of fluid dynamics, the need is to ensure that a 3D subject of great beauty is not turned into a turgid subject dominated by equations that only a percentage or so of students need in their careers. Why has fluid dynamics got a reputation for being a difficult subject? The impossibility of representing 3D fluids in motion on 2D pages of a book? It's as if not being able to deal with fluid flow behaviour caused textbook authors and academia to adopt a mathematical approach to teaching fluid dynamics. This approach is ill-suited to helping students align their extensive understanding of fluids in motion with scientific understanding.

Students' electronic devices remove many representation restrictions. This makes it possible for fluid dynamics learning to follow how fluid dynamists advance their understanding of fluids in motion. In the introduction to his book "The structure of turbulent shear flow", Townsend (43) commented, "The primary problem is to obtain from the available experimental results a clear idea of the structure and motion of turbulence. Since the experimental information is very incomplete, this process must be one of informed guess-work, followed by measurements designed to confirm the guess and then, if these are successful, by fitting into a coherent dynamical theory of the general motion."

Mohamed Gad-el-Hak reinforced Townsends' observation in "Nine decades of fluid mechanics" (44), "Perhaps more than any other tool available to tackle the complex problem of fluid mechanics, flow visualisation is singly responsible for many of the most exciting discoveries in the field." In fluid dynamic laboratories, much of the work involves building an informed guess at a good solution to a problem in the form of a physical or CFD model. This is refined by visually studying the flow in or over a physical model or the computer-generated flow representations. Another aspect of fluid mechanics laboratory activity is building physical and CFD models to investigate improving fluid systems when a designer's guess about fluid flow behaviour was wrong or never made.

Predicting the behaviour of the weather is familiar to millions through the increasing sophistication of presentations on TV and electronic devices. Forecasters run their CFD weather model based on the best available data, which is always insufficient. They then estimate the uncertainties in the starting data and run an ensemble of forecasts to indicate likely weather events. Remarkably different outcomes between forecasts occur for small changes in the input data. An ensemble indicates possible weather events days ahead. Scientists and engineers performing CFD simulations can seldom run ensemble predictions.

An understanding of fluid flow behaviour is required to estimate the inlet conditions for a CFD simulation and interpret the output.

The above comments on the importance of visualisation may seem disproportionate. Where is the mathematical rigour? Academic fluid dynamicists have mathematical backgrounds that students who intend to advance to higher fluid dynamics levels must acquire. A graduate student completing a PhD in fluid mechanics may attend more mathematics lectures than those in their primary subject. Introductory fluid mechanics courses may be given to hundreds of students, including pre-medical and general science students, who may never take another dedicated fluid dynamics course. These students should be sensitised to the fluid dynamic situations they may encounter in their careers. Had the researchers who carried out the studies subjected to due diligence reviews in Appendix C been able to visualise flow behaviour, they would likely have set up their experiments differently and made valid measurements.

Students who, as professionals, specialise in simulating flows in the natural and built environment are likely to use CFD software with a 40-year development history with, in some cases, 1000s of person-years of development. Typical advice for users (45) "Don't be seduced into believing that the solution is correct just because it has converged and produced high-quality colour plots (or even seductive video presentations) of the CFD simulations. Make sure that an elementary interpretation of the flow-field explains the fluid behaviour and that the trends of the flow analysis can be reconciled with a simple view of the flow."

7.2 Background to Multimedia for fluid mechanics

In the 1960s, the National Committee for Fluid Mechanics Films in the USA, under the guidance of Shapiro (46), produced what, at the time, were ground-breaking films on aspects of fluid flow behaviour. Ideally, the films would have been updated and extended over the years to become a suite of interactive multimedia tools. Each film stood on its own, whereas the need is for integrated multimedia resources. Each part needs to be part of an overall dynamic storyboard. This dynamic storyboard requires a keeper formed by a group/s of authoritative fluid mechanics stakeholders (Section 9).

Every year at the American Physical Society's Division of Fluid Dynamics meeting, there is a competition to find those who made videos that are "a visual record of the aesthetic and science of contemporary fluid mechanics, to be shared both with fellow researchers and the general public." (47). Submissions are judged on their combination of striking visual qualities and scientific interest. The quality of the videos and the ingenuity in recording dynamic events is outstanding. They demonstrate the academic community's ability to produce high-quality videos of fluid flow behaviour. Extending this capability to produce multimedia learning materials is a significant undertaking. A team of producers, science writers, concept animators and web and media experts is needed, such as NASA deploys to "advance their research and to support outbound communication and scholarly work." (48). Bringing into being and supporting multimedia tools for fluid mechanics and other subjects requires a new form of funding and infrastructure (Section 9).

Awareness of the need for low-cost access to high-quality instructional materials is growing. The US Department of Education funds pilot programs that support projects at higher education institutions to create easy and open access to instructional material (49). Proposed projects must meet several priorities, one of which is "an applicant must propose a project that focuses on improving instruction and student learning outcomes by integrating technology-based strategies, such as artificial intelligence and adaptive learning, with the open textbooks proposed for development to provide personalized learning experiences. These technologies must be capable of supporting ongoing electronic assessments that enable students to monitor their own learning mastery and/or allow instructors to monitor the individual performance of each student in the classes or courses for which the applicant proposes to develop open textbooks."

At this early stage of the US Department of Education pilot program, there is no indication of an understanding of the task's enormity for fluid dynamics. A starting point is fluid mechanics textbooks currently used at leading research-intensive universities (50). These books are targeted at lecturers teaching large cohorts of physics and engineering students. A typical textbook contains about 800 pages, 800 numbered equations and 1000 end-of-chapter examples that lectures can set for homework through a textbook publisher's paywall. Textbooks are updated every two years or so, mainly by adding additional homework questions so that students must buy the latest version to complete homework. A lecturer having structured a course on a particular textbook requires sound reasons to change the textbook. An objective for fluid dynamics AI inductive learning and multimedia tools should be to provide such benefits that it is to the lecturer's advantage to adopt the tools.

Textbook author/s can only be knowledgeable about limited areas of the vast subject of fluid mechanics. Consequently, authors are unaware of the current state-of-the-art in many subject areas essential to science, industry, and society. With advances in semantic publishing, information can be searched for online. Lecturers should be able to assemble textbooks in their subject area. Textbook publishers can be expected to use advances in semantic publishing to make their fluid dynamics textbooks computer-searchable and linked to other relevant subject textbooks. However, this will not update textbook content to that needed for the twenty-first century.

8. Introductory fluid mechanics learning

The following comments relate to preliminary fluid mechanics courses, including students who take no further fluid dynamics courses. Students who take further courses should learn to think critically about flow behaviour in any situation. Considerable thought is needed to determine what students should be expected to learn in introductory fluid mechanics courses. Recent studies have explained the tyranny of inappropriate and excessive content (51, 52). Excessive and inappropriate subject contents are particularly acute in fluid dynamics. It is an active research area with new material added without phasing out unnecessary material and incorporating state-of-the-art material.

Lecturers need to be honest with students regarding the state of fluid dynamics. Not being able to use Newton's laws in the form of the Navier-Stokes equation to solve everyday flow situations turns fluid dynamics into a science heavily dependent on experiments and computational methods and the ability to visualise fluid behaviour in the mind's eye. An example of the difficulty of the subject is fluid mechanics textbooks that quote Bernoulli's theorem to explain how aircraft fly. Even Einstein admitted his excursion into designing an aircraft wing, using essentially Bernoulli's theory, was a "youthful folly" (53). Sufficient air must be displaced downwards to support an aircraft in flight. Approximately 50% of engine power is used to deflect air downwards, and the rest overcomes drag at optimum flight speed (53). Aerobatic aircraft may have symmetrical top and bottom wing surfaces for similar flying characteristics inverted as normal flight, so using Bernoulli’s theorem would predict that the aircraft would not fly. Flaps and other devices must deflect sufficient air downwards at low speed to support an aircraft. Fluid flows, such as those involved in flight, involve interdependent processes that cannot be described succinctly (53). Physical, mathematical and CFD simulations account for interdependent phenomena.

The development of understanding of turbulent flows is worthy of the comment that "physics-based engineering of fluid systems is a highwater mark of human achievement" (6). State-of-the-art supercomputers, advanced software techniques, laser anemometry and experimental facilities combined with talented minds deployed to understand turbulent flows. How can students in introductory physics courses be inspired by a view of this world of remarkable human achievement?

There are few means to reveal complex fluid motions at the system level and present them in a form that can be easily comprehended. The main flow visualisation methods use solid tracer particles, fine bubbles, dye in water, and smoke and vaporised fluid in air. In studying turbulent flows at the system level, the rapid diffusion of the visualisation medium often prevents detailed examination. However, this diffusion is of interest in situations such as the spread of viruses. Researchers have developed techniques that support the film industry for realistic 3D dynamic flow simulations beyond the studios' capabilities to stage (54). Therefore, creating animated videos of internal and external complex flows is feasible. Valid and invalid fluid flow mental models were acquired in the 3D world. Replacing invalid models is challenging and should not be made more difficult by expecting students with extensive gaming experience in the 3D world to reduce general 3D experiences to two dimensions (55).

Most practical calculations of turbulent flows involve time-averaged 1D velocity profiles. Highly complex 3D turbulent flows containing structures that vary in space and time are subsumed into 1D coefficients (friction, lift, drag, head loss, discharge, contraction etc.). Students must understand what is subsumed into the coefficients. They should learn how a coefficient generated under specified conditions is adjusted to apply to other situations. The conditions include upstream and downstream flow behaviour and the Reynolds number. Coefficients are used with the conservation equations of mass, momentum, energy, and non-dimensional numbers. Extensive research exists on improving students' understanding of the application of conservation equations and the ratio of a pair of forces that non-dimensional numbers represent.

Recent research has shown that rather than simply using visual representation for conceptual understanding and knowledge generation, the aim should be for students to see how science works (56). Students are more likely to retain and use the knowledge gained if they know how it is generated. As fluid dynamics is an active research area, students should be allowed to learn how scientists work. Ideally, when appropriate, public-funded research studies should provide deliverables that qualify as part of a fluid dynamics storyboard. Students could be exposed to scientific activities at the frontiers of research, and researchers would have the satisfaction of their activities contributing to student understanding. Students, as graduates, are likely future users of research results. Demonstrating why researchers choose a particular investigative strategy would provide insights into the importance of informed guesses in advancing fluid dynamic understanding. It should also illustrate how the variables were established, controlled, and monitored for researchers to practice due diligence.

The onus is on academia and other stakeholders to turn fluid dynamics from a subject many students expect to do poorly into an exciting subject in which they achieve profound understanding and pleasure at the insights gained that will be with them for a lifetime. These observations are supported by Benoit Cushman-Roisin (57), who campaigns against those who consider students should be "forced to wade through intimidating three-dimensional partial differential equations. I know; I have been through it, first as a student and then as a professor. Maths too easily seeps into fluid mechanics until equations splash on every page and tears flow from tired eyes. The attraction of fluid mechanics textbooks today begins and ends with its cover."

8.1 Laboratory studies

Current introductory fluid systems laboratory equipment mainly involves water flows. Major hydraulics laboratories were established more than 100 years ago. With changing priorities, hydraulic laboratories diversified, and by the 1960s, hydraulic research activities had ceased at many universities. Introducing charges for university floor space resulted in university engineering departments opting for small-scale laboratory equipment that took up the minimum floor area. For the reasons given below, using this equipment causes students to acquire flawed mental models of fluid flow behaviour. They also see fluid system layouts that are bad practices in industrial situations but acceptable in domestic situations where fluid systems operate infrequently and convenience rather than efficiency is essential.

Every location in a fluid system is in the wake of components upstream of that location. A hundred years ago, Durand, in a textbook, "Hydraulics of pipelines" (58), described how the disturbance caused by a bend extended 50 to 100 pipe diameters downstream. The current laboratory equipment and the instructions for its use do not account for this flow behaviour. Laboratory aerodynamics wind tunnels provide a conditioned airflow over a model. In the 1970s, incidents of small aircraft losing control after flying into the wake 5 km or more behind large passenger aircraft focused attention on wakes. Wind tunnel simulation of aircraft wakes is impractical. Wake experiments were conducted at full scale and altitudes, allowing the wake-affected aircraft to recover control (59). Wherever we are in the atmospheric boundary layer, we are in a wake caused by upstream topography. It should be second nature to consider what is happening upstream and downstream of any location, whether internal or external.

An example of neglecting wake effects is an experiment that students carry out on an orifice plate using commercial laboratory equipment. The orifice plate is located a few pipe diameters from a T-junction or other severely wake-generating component. The experiment demonstrates the change in static pressures caused by an orifice plate. However, in the instructions, no mention is made that the performance of an orifice flow meter can depend on a component over hundred pipe diameters upstream. Students should understand the history of developing International Standards for pressure differential flow meters. In the case of orifice plate flowmeters, several billion dollars of products pass through custody orifice plate meters daily; some pass through multiple meters before reaching the user. It took over 50 years and involved building national flow laboratories and cross-correlation between flow laboratories to agree on an international orifice plate meter standard.

Adverse pressure gradients are concepts that need to be embedded in thinking about fluid flow behaviour. Internal and exterior flow situations involve one or more adverse pressure gradients. Rotodynamic pumps, fans and compressors have motors that convert electrical energy to mechanical energy and then to kinetic energy, which is converted to pressure in diffusing passageways. Low energy fluid in the boundary layer close to the passage wall entering a rising static pressure zone:

- It must be energised by the fluid further from the wall to prevent separation. With a significant boundary layer thickness at the inlet to a diffusing passage, gentle diffusion is required to avoid separation
- Move laterally towards a lower pressure region. In internal flow, low energy fluid moves towards the low-pressure region on the inside of a bend. The flow over aircraft and bird wings has a lateral component as air, at higher pressure under a wing than on top of a wing, causes movement that gives rise to contra-rotating vortices. Boundary layer flow moving laterally always give rise to secondary flows. Secondary flows are slowly damped so that they can be detected far downstream, or in the case of aircraft wing tip vortices persisting for minutes
- Separate from the wall when complex and violent transient stall conditions can occur.

The number of industrial studies involving diffusing flows may exceed all other internal flow studies. Study aims include:

- Maximum head recovery in the available space. Particularly in fluid machines such as gas turbines and axial compressors, which may have hundreds of diffusing passageways.
- An acceptable velocity distribution into process equipment or fluid machine
- Create high download on racing cars with underside floor diffusion.

Semi-organised structures in turbulent flows can have lengths much longer than the flow paths through a component. Pressure gradients acting on structures can dramatically change the secondary flow patterns within and downstream of a component. These changes give rise to pressure fluctuations that propagate upstream and downstream.

There is a need for a new generation of fluid dynamics laboratory equipment with which small groups of students can independently perform scaffolded experiments. Given that preliminary fluid mechanics is taught to many who do not take further fluid dynamic courses, developing personal fluid dynamic knowledge would seem sensible. In addition, experiments can exploit the increasing number of sensors linked to personal electronic devices for health monitoring. Physical models of the human cardiovascular system exist, and different disciplines cooperate in researching their flows (60), including the development of CFD models. Cardiovascular flows can be related to numerous industrial flow situations.

9. Who can bring together stakeholders to develop and support a fluid dynamics knowledge base?

Developing an open access knowledge base and tools to exploit the knowledge base is without precedent. How can we justify the initial and ongoing investments, and who would contribute? National research funding aims to provide a nation with competitive advantages. However, through UNESCO resolutions, nations have committed to encouraging open access to scientific knowledge (61). The question is how to transform this commitment into reality regarding fluid dynamics.

Scientific Societies actively encourage communication and international interactions on turbulence and CFD research. Communities of these research areas have international collaborative activities and links to industrial companies that may become stakeholders and contributors to a knowledge base. Combining and adding to factors described in this paper makes actions by Scientific Societies likely to succeed in initiating actions by research funders to direct funds to improve the application of fluid dynamic knowledge to benefit society and planet Earth.

10. Research Funders Dilemma

Convincing cases are made to fund research projects to reduce energy consumption, but proposers and funders are unaware of the constraints that invalidate their justifications for funding. In his book "Sustainable Energy – without the hot air" David MacKay (62) demonstrates that justifications for energy savings should be based on real numbers. Numerous studies justify boundary layer research by quoting applications where fluid friction accounts for significant energy consumption. Information on how any energy savings will be achieved is lacking. An example is air transport. MacKay pointed out that modern aircraft are highly optimised with 21st-century fuel consumption reductions, originating from engine efficiency improvements rather than aerodynamics. About fifty per cent of the energy deflects air downwards to stop an aircraft from falling out of the sky under cruising conditions; the other 50% overcomes drag on a highly optimised aircraft. Researchers hold the possibility of reducing drag by influencing turbulent flows. The engineering reality is that it may be possible to reduce drag through active means (63), but it is impractical to implement. Significant drag reduction requires semi-organised turbulent structures away from the aircraft surface to be modified by devices that make up the surface. From an engineering point of view, the fragility and weight of such devices, safety, and control complexity considerations rule them out in a time scale to control global warming. Regarding cars, the shapes to minimise drag are well established, but they are not car shapes that most people will buy. The ownership of sports utility vehicles with their high frontal area and hence drag has more than cancelled all the gains offered by legislation requiring lighter vehicles (64).

Another example given in research proposals is reduced friction losses in pipelines. The most energy intensive use of pipelines is oil and gas transport and water supply. Oil, gas and large-bore water pipelines must have facilities for monitoring and cleaning pigs whose passage through a pipeline would destroy any feature not integral to a pipe. Placing devices not critical to operations in process and power generation plant pipeworks is unacceptable. Failure of a device or part of a device is likely to result in debris. Typical problems with debris are jamming at the inlet to tubes in heat exchangers and other equipment with small bore passageways. Cavitation across partial blockages results in erosion and separation failure between fluid streams. Consequential losses from shutting down a process plant owing to cross-contamination may cost tens of millions of dollars. Hence only features that are an integral part of a pipe would be acceptable, and even then, consideration of the increased corrosion and accumulation of deposits would usually rule them out.

11 Funding for research into fluid system energy saving

Numerous studies by national and international organisations have shown the potential to reduce the energy consumption of existing fluid systems. Examples in reports indicate payback times between one and two years from matching fluid machines to system requirements. A realistic estimate for energy savings that can be achieved is 5 to 10% of the world's electrical energy consumption. Where savings can be made is understood, but numerous barriers exist to implementing energy saving actions (65). Research funding needs to be directed toward overcoming these barriers.

For energy saving purposes, fluid systems can be classified as benign or hazardous. Benign systems predominantly involve air and water that are close to atmospheric pressure. Although, their scope is extended to include refrigerants. Hazardous systems require formal and mandatory procedures to be followed.

11.2 Benign systems energy savings

In the USA, a vibrant market has developed for companies that provide energy efficiency services for benign fluid systems. Their primary customers are the municipal, university, school, and hospital sectors. Service providers underwrite the upfront costs of system upgrades via a long-term contract under which the future savings they generate to pay for the upgrades (66). Recent legislation in the USA provides funds to improve the energy efficiency of existing commercial buildings (67). Actions are required to encourage the global spread of energy efficient service providers.

University managers may know about the lifetime cost of fluid systems, but fluid dynamics lecturers may not.

11.3 Hazardous system energy savings

Large industrial plants using hazardous fluids are amongst the most complex systems built by humanity. They are also the largest users of electrical energy. Numerous studies have shown that energy use can be reduced by 15% or more. Once put into commission, any modification of a plant involving hazardous or large volumes of pressurised benign fluids requires formal procedures. Modifications are usually restricted to when a plant is shut down for mandatory inspection, known as a turnaround. During a turnaround, the opportunity is taken to carry out upgrades (68). Planning turnrounds is a continuous process.

A team of highly experienced engineers performs turnaround management. However, the team members and plant operating staff are unlikely to have experience assessing fluid system energy savings or making financial cases for upgrading systems. The design and construction of large plants are customarily carried out by design and construction contractors who operate internationally. They may also have a team that commissions the plants and trains operators. Expertise in simulating fluid systems in complex plants resides in relatively few engineers worldwide. Most of these engineers work for design and construction companies and have a background in ensuring a plant delivers its guaranteed performance. With uncertainties about the validity of fluid system data, generous margins on fluid machine head and flow are routinely added to ensure guarantees are met. Also, to succeed during the contract bidding stage, the fluid machines selected will likely be on a minimum cost basis or a plant owner's specification based on experiences with other plants. Again, these machines are likely to have been selected based on cost, even though machines typically cost less than 3% of lifetime costs. Minimising lifetime costs requires a different mindset than designing for minimum first costs.

A large plant can have over 2000 pumps (24). Also, numerous fans and compressors. 100 or so larger fluid machines can operate continuously and are the primary users of electricity. These machines are also the most significant concern as to reliability. At the plant management level, changing something that works is concerning and can be strongly resisted. A solid technical and financial case backed by demonstratable benefits is required. A requirement is the commitment of a company's chief Executive Officer (CEO) and an energy saving policy approved at the board level. Today large companies have well-publicised policies on actions to contribute to reducing greenhouse gas emissions. The question is how to influence CEOs and senior plant managers to upgrade their fluid management systems. The same applies to thermal power plants, which consume 7 to 15% of the electricity they generate. The public needs to be made aware of the environmental improvements possible by upgrading fluid systems so that they can influence decision makers.

There are examples in the literature of the substantial savings achieved in upgrading single fluid systems in process plants. What is needed are examples of whole plant upgrades. This requires funding fluid system upgrade teams that become knowledgeable about fluid systems and can carry out activities alongside plant turnaround teams.

12. Discussion on Part 2

Fluid dynamics is a science that relies on visualisation for understanding. Fluid dynamicists operate at the limits of mathematical capabilities to transform the understanding of fluids in motion into solvable equations or numerical representations. Introductory courses emphasise the mathematical aspects of fluid dynamics. However, this is not how practical fluid flow problems are solved in natural and built environments. Students starting preliminary fluid dynamics courses have vast, but not necessarily correct, practical knowledge of fluids in motion. This is a very different situation from other preliminary physics courses where the prior experience was mainly gained in an academic environment at school. Numerous prospectuses for preliminary fluid dynamics courses describe content that is more likely to destroy rather than build students' confidence in adapting their practical understanding to scientific understanding. Course content can be interpreted as reflecting the academic background of their lecturers and "entrenched departmental traditions that make little educational sense" (52). Most graduates in their careers need a practical understanding of fluids in motion and knowledge to know when they should consult a fluid dynamics specialist. Large areas of fluid dynamics require highly specialised knowledge, and it is sensible to seek this knowledge.

Fluid dynamic researchers must adopt the practice of confirming that they have carried out due diligence. Including an error analysis is a general requirement for the publication of research papers. This is a pointless requirement if the flow variables are uncontrolled or unknown. The responsibility for ensuring due diligence is carried out and a contribution to science must rest with the authors. The flawed experimental work subject to due diligence in Part 1 contains errors and omissions that a group of STEM students carrying out final year capstone projects could be expected to identify. STEM students represent a vast resource and probably the only resource that, under guidance, can sift through the fluid mechanics literature to identify validatable data and valid observations of fluid flow behaviour and find anomalies that need investigation. Carrying out such a capstone task would be an intensive learning experience, particularly for those intending to become fluid dynamic researchers. Capstone projects could be conducted internationally under the guidance of a grouping of fluid mechanics stakeholders. Fluid dynamics lecturers would have the opportunity to build an international reputation for the success of their students in contributing to a fluid dynamics knowledge base.

Knowing that groups of students are likely to review a publication may stem the publication of shoddy fluid dynamics work. As Mohamed Gad-el Hak points out, "But with the deluge of new journals, enough shoddy work is now being done to fill whole journals. Hopping from one journal to another until something is eventually accepted for publication is fast becoming a pastime for some researchers." (69).

The steady flow of single-phase Newtonian fluids in fluid systems is discussed in this study. Students should be exposed to memorable multimedia at the introductory fluid mechanics stage for various fluid phenomena, including cavitation, non-Newtonian, multi-phase, and multi-physics flows and the transient behaviour of fluids in motion. An objective of exposure to important areas of fluid dynamics is to enhance understanding of areas where specialists need to be consulted.

12. Conclusions

Society should receive an appropriate return for its investment in funding fluid dynamics research. To have allowed over 5% o of the world's electrical generation to be unnecessarily used in powering fluid systems is indefensible. A new paradigm is required to bring into being the infrastructure that supports a validated fluid dynamics knowledge base and tools to exploit the knowledge base. Less than the optimal design of fluid systems pollutes the air we breathe, adds to global warming, and reduces the efficiency of processes and products. It is in society's interest to fund the means to develop a knowledge base and tools to exploit it globally.

Scientific and engineering societies can use their influence to generate support from governments and research funders to stimulate the application of existing fluid dynamic knowledge to reduce unnecessary electrical energy consumption and improve processes and products.

Boundary layer researchers need access to high-accuracy research facilities to determine fluid dynamics parameters used in numerous CFD calculations.

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I have drawn on numerous information sources not included in the references. I am indebted to the authors of these sources.

I have likely misinterpreted research work and drawn the wrong conclusions. I hope due diligence is done on this study to correct my misinterpretations.

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Appendix A Fluid System Accidents

A.1 Introduction

Every year accidents that breach fluid system containments kill, maim, cause long-term health problems and damage the environment. A single fluid system accident can result in multiple deaths and cost billions of dollars. Such accidents are categorised into industrial sectors. They also need to be categorised as fluid system accidents to highlight the importance of fluid system events in a significant percentage of major industrial accidents.

Fluid system accidents predominately occur because of errors in judgement and not because of errors in calculations. Fluid system containments are designed using well-proven mandatory pressure containment codes. Errors in judgment result in conditions that invalidate the assumptions made in applying pressure containment codes, the means of pressure release or controlling pressures. There are conflicting philosophies regarding why accidents occur and strategies to reduce risks (70, 71). It is agreed that the unquestionable guard against accidents is that actors and stakeholders have appropriate competencies and capabilities and organisations that harness these competencies and capabilities. (71). These competencies include knowledge of the physical factors that academia does not consider their responsibility to provide. However, in a fast-moving technological society, STEM graduates may not have the opportunity to gain what is classed as physical competencies before acting professionally. Although acting without the necessary competencies breaches professional ethics codes, individuals may be unaware of their deficiencies.

The USA Chemical Safety and Hazard Investigation Board (CSB) reports on major accidents are usually accompanied by informative video animations of events that led to an accident (72). These videos show that the physical factors contributing to accidents in high-tech environments can be banal. An example is assuming that a shut valve isolates parts of a system (a valve may leak). However, although the final event in a long trail of events leading to an accident may seem banal, complex societal technical factors are usually involved in leading up to an accident. These events can be deduced by individuals who think critically about fluid systems. From hundreds of documented global fluid system accidents, a catalogue of causes could form the basis for learning resources to encourage students to think critically about fluid system risk factors.

A 2. Examples of fluid system accidents

The brief comments below illustrate the diverse nature of fluid system accidents. They exemplify how if individuals have the competencies to visualise fluid flow situations naturally, they are much more likely to take actions that eliminate the risk of an accident and act when confronted with a troubling or escalating situation.

A.3 Challenger – Lack of mental models of fluid behaviour?

Within 0.68 seconds of ignition of the booster rockets during the launch of the Challenger spacecraft on January 28, 1986, the primary and secondary O ring seals between two sections of one of the two solid-fuel boosters were breached by hot gasses (73). This led to the disintegration of the launch vehicle at 17 seconds, with the death of the 7 crew members and an estimated 3.5 billion dollar cost. Upon ignition, the booster rocket became a pressure vessel. Pressure acted to displace zinc chromate putty in a passageway to the primary O ring seal. The putty was supposed to move an O ring to seal the annular gap between two sections of a booster rocket and prevent combustion gases from reaching a seal. The putty was called a field joint, as it was made during the assembly of booster sections near the launch pad. It was impractical to create a field joint free of small faults. Faults allowed hot gasses to reach the primary O ring, and although typically eroding a third or so of the primary O ring, a seal was made. However, on the day of the challenger launch, the low temperatures resulted in the O ring resilience being too low for the seal to respond and move to seal the joint between the rocket sections. Primary and secondary seals failed.

The joint between the booster rocket sections and the sealing arrangement were bad designs. This had been known for several years, but actions to correct the problem had not been sufficiently prioritised. Reports on the disaster highlighted numerous political, budgetary, and contractual factors combined with senior management's lack of technical understanding. The decision to launch Challenger was against technical advice that it should be delayed until seal temperatures had risen, but carrying out launches knowing that the O ring seals would be damaged had become a normalised routine.

One can only postulate that the Challenger accident would not have happened if more of the numerous individuals connected to the space program had naturally formed mental models of fluid flow situations. One of the many moral failings was not telling the NASA Astronaut Corps of the problem with the O rings. Before the Challenger accident, some Corps had flown missions in which hot gases had penetrated the primary O ring seal. They would not have allowed launches if they had known about the O ring problem (74). Unfortunately, many plant operating staff have died from fluid system accidents. Some, such as the astronauts, would have been unaware of the fluid system failure risk. Company management cannot abrogate their responsibilities to ensure that operators have the competencies and the delegated authority to preserve their and others' lives. Universities should enable students to learn about their responsibilities regarding others and their safety.

A.4 Three Mile Island – Understanding what control panel signals indicate

On March 28, 1979, a minor fault in the secondary cooling circuit caused the TM-2 nuclear reactor to trip. Within 1 second, the reactor shut down automatically, and a relief valve opened to relieve the pressure in the cooling circuit as the temperature increased. The relief valve failed to close when the pressure dropped, allowing so much of the primary coolant to vent that decay heat was not removed from the reactor core and the core partially melted. The relief valve was operated using a solenoid. At the design stage, it had been assumed that the on/off signal to the solenoid could indicate the valve position (75). Operators had not been trained about what information they were presented with and its origins and assumed that the relief valve was closed. They did not take actions appropriate for an open relief valve.

Safety reviews should have identified the need for a relief valve position indicator. However, important details can be overlooked even in a safety review. The Three Mile Island accident highlighted the need for operators to be trained to question and understand what information they are provided with and where it originates and given the authority to require that it is adequate for them to carry out their responsibilities.

A.5 The most costly accidents in terms of lives lost, environmental damage and costs.

The world's worst loss of live industrial disaster occurred in 1984 in the Indian city of Bhopal (76) "which saw 40 tons of toxic gas released into the air, killing over 3,000 instantly and condemning hundreds of thousands to a future of prolonged pain, cancer, stillbirths, miscarriages, lung and heart disease and the drawn out deaths of everyone around them" (77). It is postulated that relatively small amounts of water from cleaning operations remote from a methyl isocyanate storage vessel travelled through piping to the storage vessel, possibly through a valve that leaked. This caused a runaway reaction. All safety systems that should have prevented the reaction and those that should have flared the poison gas generated were inoperable. There was no need to store methyl isocyanate. It can be manufactured as required.

Bhopal was a wake-up call to the world's chemical industry on safety. However, actions were not always taken to eliminate the storage of dangerous intermediate chemicals. In 2012 the CSB pointed out that an explosion in a chemical process complex in the USA (78) could have damaged piping to a methyl isocyanate storage tank similar to that at Bhopal and caused a major disaster. This highlights the importance of sensitising students to fluid system safety, particularly those who may become company directors or influencers in the design and operation of fluid systems.

The world's worst environmental disaster was the BP Deepwater Horizon Oil Spill on April 20, 2010, which cost 11 lives directly and BP $ 61 billion. It continues to have severe consequences for the environment, people's well-being and livelihoods. An extensive catalogue of technical problems included not considering known problems with the deflection of drill strings inside a casing, elementary errors in the design and the inability to test the ultimate safety system, the blowout preventer. Financial pressures to complete well abandonment contributed to the catastrophic accident (79).

When a blowout was evident, the operator diverted the flow into a gas separator, which was overwhelmed and led to an explosion. Had the flow from the well been diverted overboard on the downwind side of the drilling vessel, an explosion that killed drilling staff and severed connections to the blowout preventer on the sea floor would not have occurred. This may have saved lives but possibly not the environment. An operator should not have been placed in the position of making a split-second decision because of faulty decisions made over many years up to the company board level.

A.6 Conclusions

Complex fluid systems fail in complex ways, typically through a chain of what investigators find were decisions made over many years. A factor agreed that avoids faulty decision chains is individuals having appropriate competencies and capabilities and organisations that harness these competencies and capabilities. STEM and social sciences students should learn more about their health and safety responsibilities.

Appendix B Due diligence review of Colebrook and White's and Colebrook's Papers

B.1 Colebrook's downgrading of Nikuradse's transitional friction factor curves

In 2010 turbulence researchers from six universities conducted a wide-ranging review of recent advances and key issues related to high Reynolds number flows over surfaces (8). They wrote, "New roughness experiments have shown that most (but not all) roughness types produce an inflectional (Nikuradse-like) transitional resistance relationship. While Nikuradse's results in rough-wall flows are for the specific sand-grain roughness, they are far more representative of the practical conditions than any of the Colebrook correlations, which are smoothed curves through a variety of practical conditions, but not accurately representative of any of them. This implies that schemes based on Colebrook's interpolation (such as the Moody diagram) have to be phased out gracefully".

In a study published in 1939, Colebrook (13) concluded that sand grain roughness used by Nikuradse did not represent actual pipe surfaces. He used the results from a 1937 paper by Colebrook and White (12) to support his conclusion. These studies are amongst the most referenced fluid mechanics studies. Being highly referenced, one would expect the studies to have been researched many times to understand the experimental methods, data generated, and the validity of conclusions. The author is unaware that the studies have been subject to such scrutiny and the results published. It can be shown that friction factors in the Colebrook and White study were fabricated. Correctly interpreted, the experimental results support Nikuradse's transitional resistance relationship. Nikuradse's work is considered first.

It should be noted that from the writing style and the number of assumptions made without scientific evidence, it is reasonable to conclude that Colebrook wrote both papers and performed the experimental work. As described in Section 2, White's experimental work was meticulously executed and reported. Colebrook's confident presentation style gives the impression of validity to sweeping statements unsupported by experimental evidence.

B.2 Nikuradse Experiments

Nikuradse's experimental work was conducted in Prandtl's research group in the early 1930s (14). The group had been at the forefront of research on turbulent flows for over ten years. They had proven experimental facilities for researching pipe friction factors using water as the working fluid.

Nikuradse's experiments involved three pipe diameters, 25 mm, 50 mm and 100 mm. Pipe internal surfaces were coated with building sand particles, providing six pipe-to-particle diameter ratios. Sand particles were sieved to narrow size bands. From the photograph in the report, the sand appears to be sub-rounded with variable aspect ratios and sharp edges.

An elaborate particle attachment procedure was developed to prevent particles from washing off pipe surfaces. This procedure left the particles coated with a layer of lacquer. Nikuradse determined that the lacquer thickness did not significantly affect particle projection from a surface. He used the same lacquer to attach particles to a flat plate and then measured the particle projection height. The projection heights were essentially the same with and without lacquer. As generally assumed, this was not a check of the roughness height within the pipes. The orientation of the longest axis of a particle would have tended to be parallel to the plate surface and not random as in the test pipes. Nikuradse stood his pipes vertically and filled them with Japanese lacquer. Drained the lacquer, and when the lacquer was tacky, filled a pipe with a mixture of sand and white lacquer. This was allowed to flow out from the bottom of the pipe. After the drying period, the pipe was refilled with a thin lacquer, drained and followed by a drying period. The procedure would have resulted in the longitudinal axis of particles being random with gaps between particles. The roughness element heights would have been less than the sieve pore size, up to approximately twice the pore size; elongated particles with sharp edges have variable radial dimensions, some of which are considerably smaller than the sieve pore dimension.

Nikuradse used the term “uniform sand grain roughness”. This term has been widely interpreted to mean that the roughness was of a uniform height, whereas this would not have been the case; the particle geometries varied considerably. Some investigators have assumed that sand particles are spherical, whereas building sand particles have to be non-spherical with sharp edges to provide mortar holding strength.

Using the two-layer lacquer procedure, Nikuradse conducted endurance flow trials at water velocities of 20 m/s to confirm particle attachment. The author considers this a remarkably high velocity for a not-very-strong attachment procedure if the attachment is by a thin layer of lacquer. This could be because hardened lacquer filled much of the space between particles. Surface tension retaining lacquer during the lacquer coating procedure. Three to four weeks were necessary for the lacquer to harden, even though air circulation was maintained through a pipe to aid drying. The long drying time indicates thick areas of the lacquer. The uncertainty of how lacquer partially filled the space between particles, the geometric differences between particles, and their spacing mean the only sensible description is "Nikuradse's sand roughness". Section 5.2 discusses actions to provide defined surrogates for Nikuradse's sand roughness.

Nikuradse determined the mean pipe diameters from the weight of water required to fill a pipe and the pipe length. For larger roughness values, the friction factors were higher than those obtained if based on a physical pipe diameter measurement across roughness elements.

B.3 Limitations on experimental Reynolds number ranges

Industrial turbulent flows span five orders of magnitude of the Reynolds number from approximately $3x10^3$ to above 10^8. The transition from a hydraulically smooth to a hydrodynamically rough surface condition occurs over more than an order of Reynolds numbers (based on Nikuradse's measurements and recent experiments). Using water and air at normal temperatures and pressures, most friction measurements in laboratories and operating systems have covered less than one order of magnitude of the Reynolds number, with approximately a 100:1 variation in the head difference.

When tests are carried out using water from a constant head source, and flow rates are established by weight or volume, a 20:1 Reynolds number range is practical within a laboratory environment. With good head differential measurement and flow rate measuring capabilities combined with exceptional flow-generating means, a Reynolds numbers range of 30:1 is achievable. Nikuradse exceeded this Reynolds number range, in one case, raising the temperature of the water to achieve higher Reynolds numbers.

When a fan powers a test rig with a stable head/flow characteristic, a 3:1 Reynolds number range is practical when the flow rate is controlled by throttling the fan discharge. Using air bleeds to enable a fan to operate close to its design point makes the 5:1 Reynolds number range realistic. If a high-quality variable speed controls the fan drive, a 5:1 to 10:1 Reynolds number range is possible.

B.4 Colebrook and White experiments

Colebrook and White's test rig consisted of a pipe test section connected to a fan inlet, Figure B 1. The fan is shown as being directly coupled to the motor. There is no mention of a variable speed drive or how the flow rate was controlled. Based on this evidence, the flow rate control was probably throttling the fan outlet. In this case, a reasonable Reynolds number range would be 3:1. For the comments that follow a variable speed drive providing a 10:1 Reynolds number range were assumed.

In Colebrook and Whites, friction factors are tabulated and plotted over Reynolds number ranges of 23:1 to 38:1. These are impractical Reynolds number ranges for the test facility. The head differentials and air velocities can be calculated from the information provided, assuming normal temperatures and pressures. The pressure differential across the flow metering nozzle would have been less than 50 µm water gauge at the lowest Reynolds numbers quoted. A manometer reading accuracy of 0.5 mm would be expected, provided flow instabilities were small.

B.5 The test facility

A pipe 53.5 mm in diameter and approximately 6 m long was split longitudinally to allow sand grains 0.35 mm and 3.5 mm to be attached in five arrangements to the inner surface, Fig B 2. Sand grain attachment was presumably achieved by pressing particles into a coating on the pipe wall with approximately a quarter to a third of a particle pressed into the coating, as indicated by a representation of a "typical large grain" shown in Figure B 3. The pipe material was not specified, nor how it was split. It was probably a metal pipe sawn longitudinally. When the two halves were clamped together and sealed with adhesive tape, the flow cross-section would not have been a true circle, and the cross-sectional area would have been reduced.

The inlet flow metering nozzle was cast in paraffin wax and calibrated against the pressure loss over the test length of 50 pipe diameters. The pipe was assumed to be hydrodynamically smooth. It is not specified whether this was done before or after the pipe was split. The flow nozzle calibration should have been verified by integrating detailed velocity profiles.

Preliminary trials showed "that entrance effects extended downstream rather further than had been anticipated. It was considered advisable, therefore, to insert a diffusing baffle near the inlet to ensure the development of the ultimate velocity distribution before reaching the test length". The test pipe had two static pressure tapping locations, one at 50 diameters from the inlet nozzle and the other at 100 diameters from the inlet at the end of the test section Figure B1. Entrance effects could not have been detected with these tappings. Nikuradse established that inlet pipe lengths of 30 diameters for 25 and 50mm diameter pipes and 40 diameters for his 100mm pipes were sufficient to avoid inlet length effects. An inlet length of 50 diameters should have been sufficient to establish a steady friction gradient. No description of the diffusing baffle or where it was located was provided. The performance of a diffusing baffle would have been Reynolds number dependent and produced an unknown level of turbulence and velocity distribution at the start of the test section.

Four interconnected wall static pressure tappings measured static pressures. It was commented that "the errors of individual holes as shown by tests of each one against a neighbour at the same section were fortunately negligible". This contradicts the author's experience based on numerous experiments involving hundreds of static pressure tappings. Errors of up to 25% of the velocity head could be expected in rough pipes. Nikuradse used miniature static pressure probes to avoid this problem, commenting that "marked errors result if piezometer holes in walls of the pipe are used in rough pipes".

Curve I of the test results, Figure B 3, relates to 0.35mm diameter particles covering the pipe wall. Curves II to V relate to surfaces with approximately 0.5-2% (based on scaling from Fig B 2) of the surface covered by 3.5 mm diameter sand particles and 0.35 mm diameter particles covering from zero to the remainder of the surface. The particles were fixed by bituminous paint or Chatterton's compound. It is probable that the 0.35 mm particles for curve I were embedded in a coating of bituminous paint. The tests that generated curves II to V had particles embedded in what can be assumed was a 1 mm or so thick layer of Chatterton's compound, a quarter to a third of the 3.5mm particle height. Chatterton's compound is supplied in bar form and heated to be used. How static pressure tapings were formed through the Chatterton compound is not described, nor how a uniform, smooth coating of approximately 1 mm thickness was achieved. The representation of a typical large grain Fig 5 shows grains bedded on the surface of the Chatterton compound.

B.6 Friction factor curve displacement

Assuming CW's loss coefficient curves, Figure B 3 at Reynolds numbers above 10^4 are based on actual measurements, then curves I to V can be interpreted as having a similar inflectional shape to those of Nikuradse but with curves II to V displaced upwards. For the size and distribution of the roughness elements, the upward displacement is more than expected from Nikuradse's studies.

If a 1 mm or so thick coating of Chatterton's compound was used, items 1 and 5 above, the reduction in the 53.5 mm pipe diameter caused by such a coating would be approximately 4%. Given that head loss varies roughly as the inverse of the diameter to the fifth power, the reduction in pipe diameter would have resulted in an upward displacement of the friction curves by over 20%.

The details of the order in which the tests were performed are not provided. Assuming that test I was followed by removing the smaller particles or covering up the particles with Chatterton's compound, the logical test order would have been V, IV and III and then removing some larger particles for test II. Such a sequence does not account for curve II not coinciding with curves III-V in the region where the curves could have been expected to lie on and depart from the hydrodynamically smooth curve. Another test sequence, or a static pressure tapping error change, could have been involved.

As Colebrook would not have been able to measure the mean flow cross-sectional area, it is reasonable to conclude that Colebrook's friction facto curves II to V were calculated based on the pipe diameter (with or without correction for material lost in splitting the pipe) and not a reduced diameter due to a layer of Chatterton's compound. If the mean pipe diameter had been used, the curves would likely initially followed and departed from the smooth pipe curve as the Reynolds numbers increased.

B.7 Colebrook-White equation

In his 1939 paper, Colebrook adopted an implicit equation to calculate friction factors. To justify the equation, he made several assumptions based on data from the 1937 Colbrook White study and friction factor versus Reynolds number curves from the literature. He concluded, "It is apparent that with non-uniform roughness, the transition zone extends over a range about 10 times as long as that for uniform sand roughness, and in the case of new commercial pipes in which the roughness is non-uniform, the whole working range lies within the transition zone".

Numerous friction factor versus Reynolds number curves were available in the literature at the time of Colebrook's study. Nikuradse plotted 33 curves of measured friction factors from the literature (14). Most covered a Reynolds number range less than 10:1. No conclusions on friction factor trends with Reynolds numbers could be drawn from the curves because of the limited range of Reynolds numbers covered. Colebrook had the same problem of data from the literature only covering a limited Reynolds number range. However, he assumed that the shape of curve V from the 1937 paper, Figure B3, indicated that at the highest Reynolds numbers, hydrodynamically rough (square law) pipe conditions had been reached "thus with many of the test results it is possible to extend them with very little error to reach square-law and enable the determination of the k values". As pointed out above, rather than reaching fully rough conditions, it is highly likely that curve V, at the highest Reynolds numbers, had only started to diverge from the fluid dynamically smooth line.

In Figure 1 of the Colebrook and White paper (Figure B4), two friction factor curves from the literature were extrapolated by assigning relative roughness values without evidence of the actual pipe roughness or how friction factors varied with the Reynolds number. Colebrook adopted curves of the same form in his 1939 paper in contradiction to the Nikuradse-shaped friction factor curves in the Colebrook and White paper.

B.8 Final Comment

Colebrook tabulated Reynolds's numbers for all his data points, including those he could not have measured. Colebrook fabricated many of his data points.

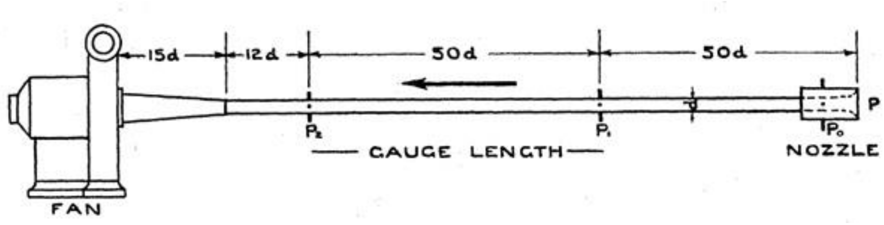

Figure B 1. Colebrook and White test rig

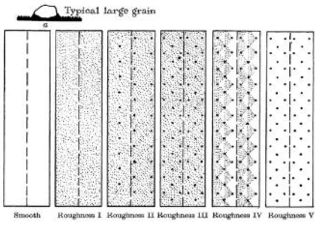

Figure B 2. Colebrook and White test surfaces

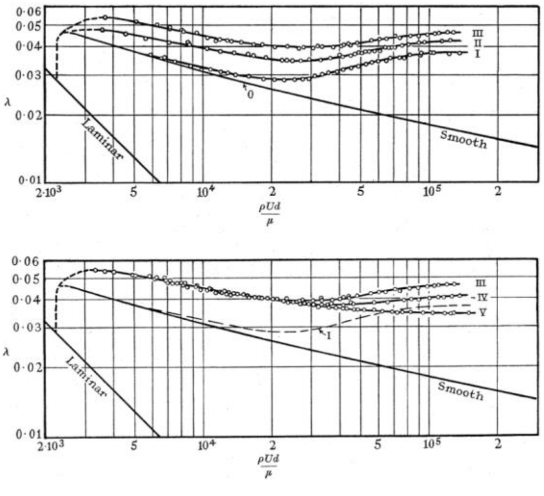

Figure B 3. Test Results

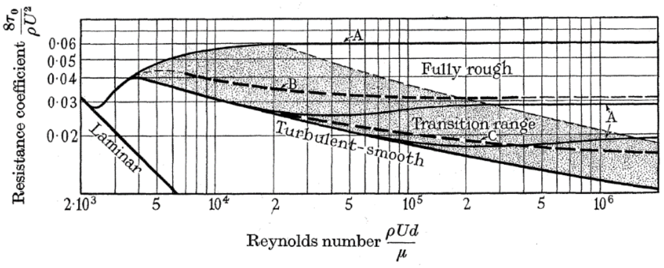

Figure B 4. Colebrook and White's Figure 1 (A curves are based on Nikuradse's work)

Appendix C Due diligence on recent projects

C.1 Introduction

Several internal flow projects have been carried out since BHRA studies ended in the 1980s. Due diligence studies of the projects provide insights into the need for guidance in planning and commissioning research facilities and carrying out and reporting experiments. Researchers must visualise events in the mind's eye to relate them to flow behaviour.

C.2 Measuring static pressures

Fluid flow experiments require measurement of the static pressure. A small, sharp-edged, defect-free hole (piezometric) is required. The viscous sublayer is only microns thick at high Reynolds numbers, requiring additional hole geometry requirements to be met (80). Numerous internal flow projects have generated erroneous results because of faulty static pressure tappings. Drill breakthrough invariably results in a burr on a flow surface. The typical method for metal pipes is honing to remove burrs. If the hole surface at the drill breakthrough is torn, honing does not result in fault free tappings. Regarding surfaces that corrode, “The worst effect of rusting, however, appears at piezometer holes. Here ridges of rust frequently build up around newly drilled holes in such a way as to falsify the pressure indications” (81).

Devising means of monitoring static pressures are correct for the duration of a test program is challenging. During the planning stage of experiments involving static pressure measurements, a document for the making, checking, and monitoring of static pressure tappings should be generated. In the due diligence studies that follow, there are questions about the validity of static pressure measurements. A recent commissioning study on the (CICLoPE) facility of the University of Bologna (82) illustrates the need for a static pressure plan. Erroneous tappings were observed during commissioning trials. Ideally, fluid dynamic research facilities should have four tappings at each location along a pipe, and a precision manometer should be used to compare these four tappings. If the tappings at a location agree within a predefined tolerance, one tapping should be selected to connect to the pressure scanning system. Multiple tappings at a location should not usually be connected, even if they record the same pressure as joints to form multiple connections increasing the risk of leakages. The CICLoPE saving grace was its large number of tappings along the pipe so that faulty tappings could be identified and neglected.

C.2 Heating and ventilation ductwork (HVAC)

In the 1980s, The European Commission funded a loss coefficient study, referred to here as the EU study, to provide accurate loss coefficient data for improving the performance of building ventilation systems. Some of the study's results are reported in (83). The study involved testing over 400 duct components by four EU research organisations. Rather than seeking to benefit from prior research, project investigators decided to adopt a new procedure for measuring loss coefficients. The procedure is unscientific. The reasons for the unscientific nature of the procedure are outlined below.

The standard for measuring loss coefficients based on the EU study is published by Europe's Industry Association for Indoor Climate Process Cooling and Food Cold Chain Technologies (EURVOENT). Its members from Europe represent more than 1,000 companies (84). The standard specifies the geometric arrangements upstream and downstream of a component under test, with downstream being the most important. "According to this standard instead of a very long duct (it may be as long as 40D) a specified flow straightener (as used for fan performance testing now applied in the ISO Standard and in many countries) is installed immediately downstream of the component under test. The correct measurement of the pressure is therefore possible whereas the loss on the straightener and associated ducting is taken into account conventionally."

"An important advantage of this method is the elimination of the necessity to measure the kinetic energy factor α_A in the upstream as well as in the downstream section. It is assumed that α_A is equal to one. If a particular component produces a very strong swirling flow with an irregular velocity distribution, the energy loss in the straightener will be far greater than the conventional value for the calculation. The energy loss coefficient of the component under test will appear higher."

Two diameters downstream of a component, an ETOILE flow straightener 2 diameters long was installed. The flow straighter has 8 vanes at 45°. Component loss coefficients were determined by measuring the total pressure drop between static pressure tapings, five duct diameters upstream of a component and five diameters downstream. Subtracted from the measured total pressure drop was the calculated Reynolds number dependent friction loss between the tapings plus a calculated Reynolds number dependent flow straightener loss.

An ETOILE flow straightener removes swirl effectively but is poor at removing flow distortion and can act to maintain it. The flow can be distorted or separated at the component outlet and swirling with or without flow separation. Interactions between the flow leaving a component and a flow straightener two diameters downstream would be highly complex, as would its effects on head losses. The effects of a flow straightener depend on the Reynolds number, flow distortion, flow separation, turbulence levels, flow instabilities and the existence and strength of single or multi-cell rotation. For instance, in (3), the variation in the swirl strength at a bend outlet and flow separation varies with bend angle, radius ratio, Reynolds numbers, and inlet velocity profile. The swirl strength initially increases with the bend angle, but by 90° is decaying and can reverse before 180° is reached. For the bends typically used in HVAC systems, the separation on the inside of a bend is reduced by secondary flows. The straightener would interfere with this process.

Raising the subject of measuring kinetic energy coefficients as a justification for the adopted method was misleading and erroneous. The conventional method of applying loss coefficients accounts for kinetic energy throughout the system, as described in Section 2.1.

ASHRAE in the US has, since the 1990s, funded studies on the loss coefficients for air handling components. The first of these studies (85), the AH study, is important because it contributed to the ASHRAE test procedure for loss coefficient measurement. The loss coefficients measured for different sized components did not lie on the same curve. It was concluded that there was a size effect in addition to the Reynolds number effects. The investigator should have concluded that the experiments were flawed because only the Reynolds number similarity must be satisfied if the geometric similarity is met. Some of the plotted AH study loss coefficients for bends were too small. Therefore, questions remain regarding the measurement accuracy of the entire project.

Koch (86) used loss coefficients from ASHRAE and AH studies to revise the 2009 edition of the Chartered Institution of Building Services Engineers (CIBSE) Handbook. He commented that the BHRA studies involved one component size. BHRA researchers had experience with numerous scale models. They verified their loss coefficient results against validatable data generated by other researchers for several component types, sizes and flow cross-sections.

Koch’s dilemma in deciding which bend/bend interaction correction factors were valid illustrates the erroneous nature of the EU study loss coefficient definition (87). The EU study correction factors were greater than one for closely spaced 90-degree bends of any configuration. The BHRA correction factors, depending on the bend orientation relative to one another, fall to as low as 0.6 and are less than one up to bend separation distance of 20 pipe diameters for all bend configurations. The BHRA correction factors agree with reliable data from several sources on bend/bend interaction correction factors.

The myth that loss coefficients depend on duct size and Reynolds number is given false credence by the practice in the HVAC industry of using single-value loss coefficients for particular sizes of components. As duct size increases, a lower coefficient is obtained, with unrealistically low values for large components in some cases.

C. 3 Bettis bend loss studies

C.3.1 Introduction

Reynolds numbers of up to $4x10^7$ were reached in the Bettis bend loss coefficient studies, which is ten times higher than in other bend loss coefficient studies. The test rigs operated with water at high temperatures and pressures to reach these Reynolds numbers. The investigators' lack of understanding of internal flow behaviour led to the excessive head loss being assigned to pipe friction. Their bend loss coefficients were too small. Understanding why the investigators did not measure what they thought they were measuring is of considerable value for future loss coefficient studies at high Reynolds numbers.

The studies mainly involved 90-degree bends with a radius-to-diameter ratio of 1.2. The loss coefficients were measured for single and closely spaced bends. Closely-spaced bend results are not reviewed here. Experiments were carried out in several stages referred to here as:

- Stage 1: Loss coefficients measured using a low-pressure test rig (88). Faulty static pressure tappings were discovered after the experiments, and the results were invalidated. However, they led to care in making Stage 2 and 3 tappings.
- Stages 2 and 3: The loss coefficients were measured using high-temperature and high-pressure test rigs.

C. 3.2 Literature review

The literature review for Phase 1 included one research paper, four handbooks and one paper on pipe fittings. The investigators did not research the experimental data sources used to prepare handbooks. This meant that they did not locate validated experimental data they could have replicated before moving on to measurements at higher Reynolds numbers.

The investigators concluded (88), "Prior to the testing to be described, the world's data base for piping elbows was limited, and these are at relatively low Reynolds numbers (0.5 x 10^6). For example, less than a dozen data points were identified to exist for 45° elbows with bend radius of curvature (r/D) less than 1.8, where irrecoverable loss effects start becoming significant. Data for 90° elbows was also found to be scarce with large inconsistencies between investigators*"*. One of the handbooks quoted was (3), which contains BHRA data. The bend loss coefficient chart in (3) covers bend angles up to 180° and bend radius to diameter ratios up to 10. The chart is for a Reynolds number of $10^{6,}$ and a plot of correction factors for other Reynolds numbers is provided. Had the Bettis investigators followed up on the references on which (3) bend loss coefficients are based, they would have found it extended to a Reynolds number of 1.2 x 10^6 and agreed with other high-quality studies.

C.3.3 Phase 2 Friction gradient errors

In the Phase 2 report (89), a plot of the loss coefficient curves against Reynolds numbers has a figure with six bend loss coefficient curves. Three curves were for loss coefficients calculated using equations applicable to pipe fittings at low Reynolds numbers and were irrelevant to the study. The loss coefficient plots of BHRA (3) and Idelchik (90) show that loss coefficients for bends with radius to pipe diameter less than 1.3 become independent of Reynolds number before 10^6. The Bettis experimental coefficients continue to decrease to the highest Reynolds number reached. Since the Bettis studies, bends with a radius to-diameter ratio of 1.5 have been tested at Reynolds numbers up to 4x10^6, Appendix C.4 The loss coefficients for bends of four different diameters became independent of Reynolds numbers below 10^6.

Bends with a radius ratio of less than 1.5 have an area of separated flow on the inside of the bend. The separation extends into the downstream pipe. The separated area appears to grow with increasing Reynolds numbers, probably because secondary flows that feed energised fluid into a separation zone weaken as Reynolds number rise; pipe velocity profiles become more uniform as Reynold numbers increase. A reduction in losses due to weaker secondary flows within a bend and an increase in separation losses probably explains why the loss coefficients for bends with radio ratios less than 1.5 become independent of Reynolds numbers before 10^6.

In the Bettis 2 experiments, the time-averaged velocity profile over the central third of the inlet pipe to the bend was measured 15 diameters downstream from the pipe inlet. Unbeknown to the investigators, the profile had an inviscid core extending from the pipe inlet. The investigators compared the inlet velocity profiles with its inviscid core to velocity profiles measured at 196 diameters from the pipe inlet in the Princeton Superpipe facility (91). The mean velocity profiles were similar. They incorrectly concluded that the flow entering the test bend was fully developed.

With an inviscid core, the apparent average friction gradient from the pipe inlet to the velocity profile measurement location can be calculated from the ratio of the pipe centreline to the mean pipe velocity. Ratios of 1.13 to 1.17 indicated friction factors of 0.0113 and 0.0087. Pressure gradients in the initial section of a pipe following a contraction are higher than developed flow gradients due to a flow’s mean kinetic energy coefficient increasing as a growing boundary layer accelerates the inviscid core flow. The friction gradients measured immediately before a bend were higher than those averaged over the first 15 pipe diameters. However, they should have been lower.

A bend outlet pipe length of 45 diameters was insufficient to establish a developed friction gradient. Too much head loss was attributed to pipe friction.

C.3.4 Phase 3 Qualification testing

The pipe diameter for Phase 3 was 177 mm, compared with 132 mm in Phase 2 (92). It had a honed surface finish of 0.25µm as for Phase 2 pipes. The test arrangement only allowed the friction gradient to be measured in the pipe to the first bend. This pipe was 23 diameters long with a flow straightener at the pipe inlet. It was commented that the flow straightener provided a fully developed turbulent velocity profile for high Reynolds number applications, which was not the case. Thirty-five jets from holes drilled in the flow straightener plate would have entered the test pipe with combined kinetic energy approximately three times that of the mean pipe kinetic energy. Intense turbulent mixing would have increased static pressure and produced a near-uniform velocity profile downstream of the flow straightener. A boundary layer would then have grown with an essentially inviscid core. The inviscid core extended to the test bend.

In Phase 3, the pipe friction frictions were estimated more accurately than in Phase 2. The investigators drew graphs of the pressure ratio versus the pipe length-to-diameter ratio. T Investigators provided sample plots of the pressure ratio versus length to diameter ratio at three Reynolds numbers. For unspecified reasons, the three plotted friction factors are below the average friction versus the Reynolds number curve in the study report.

The friction factors measured in Phase 3 were significantly lower than those in Phase 2; the roughness height to pipe diameter ratio in Phase 2 was higher than in Phase 3 but not nearly sufficient to account for the friction factor difference. Although the investigators pointed out that the friction factors were lower in Phase 3 than in Phase 2, they did not comment on the likelihood that the bend loss coefficients from Phase 2 were significantly underestimated because too much head loss had been attributed to friction.

C.4 Building water services loss coefficients

ASHRAE funded studies to measure commercial components' loss coefficients in building water services (93, 94, 95). Most studies were conducted at the University of Utah's Hydraulics Lab (UWRL), with a single study conducted at the University of Minnesota's St. Anthony Falls Laboratory (SAFL) (96). More than 700 components were tested.

Some UWRL loss coefficients were plotted against the pipe water velocity (a common practice in the HVAC industry at that time). One project report commented, “Plots of loss coefficients versus Reynolds number may be more appropriate for comparing different fitting sizes”. However, this was not performed. If the loss coefficients had been plotted against Reynolds numbers, it might have led to an investigation of why some loss coefficients did not follow logical trends.

A study at UWRL (96) included tests on 304, 406, 508 and 610 mm (12, 16, 20 and 24 inches) diameter bends (ells) with a radius to diameter ratio of 1.5. The Reynolds numbers exceeded 10^6. The UWRL loss coefficients became independent of the Reynolds number before 10^6, as found by BHRA (3). However, the loss coefficients for the bends were considerably smaller than the BHRA coefficients at 10^6. In addition, the loss coefficients for the four bends, at the same Reynolds number, differed, whereas they would have been expected to be more or less the same; because of the bend sizes, wall roughness is unlikely to have been a significant factor.

The study reported that *“fully developed pipe flow”* existed at the downstream static pressure measuring location at 12 pipe diameters after a bend. A table in the study report indicates that measurements were made approximately 6 diameters downstream of a bend. Significant effects on head losses extend approximately 30 diameters downstream of a bend, as discussed in Section 2.1. If static pressure were measured six diameters after the bends, approximately 70% of the total head loss would have been measured. This partially accounts for the low loss coefficients recorded relative to BHRA coefficients. However, it does not account for the difference in coefficients between bends of different sizes at the same Reynolds numbers.

Unrealistically low values of the loss coefficients were also recorded for tests on expanding transitions that involved the pipes used for the bend tests. For instance, a loss coefficient of 0.02 is given for a 508 to 610 mm expansion, whereas a loss coefficient above 0.08 would be expected; the expansion length to pipe radius ratio was small, making them inefficient as diffusers, so loss coefficients should have been close to those for sudden expansions.

The UWRL loss coefficients recorded for the PVC expansions were more than three times the theoretical maximum. The loss coefficient curve for threaded 50mm bends increased with water velocity/Reynolds number. This contradicts other bend loss coefficients, which decrease with increasing Reynolds numbers.

SAFL plotted their bend loss coefficient along with those of UWRL and showed those bend loss coefficients are size related. This reinforced the false assumption in the HVAC industry that loss coefficients are size and Reynolds number dependent. What they should have concluded was that there were inexplicable errors in measurements.

Measuring small negative loss coefficient for the through flow of dividing T junctions, SAFL comments indicated they were unaware of how 1D CFD calculations account for energy losses. They commented, *"*A negative K-value is unrealistic, implying a non-Bernoulli gain in energy as the flow traverses the fitting. The impossibility of such an energy gain suggests an artefact in the test procedure*"*. Flow continuing straight through a dividing junction slows down with little energy dissipation. Rising static pressure in the through flow forces low energy fluid close to the wall to flow around the junction wall and into the branch. As the mean kinetic energy of a developed turbulent flow is approximately 1.1 times that of the mean velocity, part of this kinetic energy is available in the through flow to be converted to an increase in static pressure. Upstream of a T junction, a component has been debited with energy to create a developed velocity profile. This means that there is no energy gain on a system basis.

C. 5 Steel pipe friction factors

In "The Review" (8), the observation is made that "One roughness type that does not follow this inflectional trend is the commercial steel pipe roughness studied by Langelandsvik et al." (97). The observation is based on a single steel pipe tested in the Superpipe research facility at Princeton University. Steel pipe is the most widely used material for industrial pipelines, so it is important to know if this observation is valid.

C. 5.1 Test Pipe

The steel test pipe, purchased from a wholesaler, was longitudinally welded. It was most likely hot-rolled. Extensive studies of steel pipe roughness found hot rolled pipe surface roughness ranging from R_a -4 to 26 µm measured with a roughness gauge (98). The test pipe roughness was measured using an optical technique. The root mean square roughness was approximately 5.0 µm (99). The pipe could be considered relatively smooth for welded rolled steel pipe.

C. 5.1 Superpipe measurements

The experimental work followed the high standards of the Superpipe facility except for problems with static pressure tappings. These were drilled using a technique aimed at minimising burrs. As others have found, producing fault-free static pressure holes simply drilled into the pipe is impractical when the requirement is not to do any finishing operation inside the pipe Appendix C.2. In (99), it is commented, "It is also clear that the pressure gradient uncertainty is the dominate source of uncertainty, except for the lowest Reynolds numbers. “The scatter in the pressure gradient measurements increased dramatically with Reynolds number, indicating that some burr was probably present on at least some pressure taps.”

In (97) it was assumed that at the highest Reynolds numbers, the friction factor in the steel pipe had reached the fully rough state. The published plot of experimental friction factors could be interpreted as not reaching a sufficiently high Reynolds number to show an upward transition to the fully rough condition. The friction factor measurements in (89) Appendix C.3 support this interpretation. Although the friction factors in (89) are in error, the data trends clearly show an inflexion curve for measurements at higher Reynold numbers than those reached by the superpipe experiment. The rough surface finish in (89) was achieved by sandblasting, one of the surface finishes that steel pipe producers provide (98).

Appendix D. Research facilities to determine subtle fluid flow behaviour

Several pipe-based research facilities have recently been constructed to study wall-bounded turbulent flows at high Reynolds numbers. The Superpipe facility at Princeton University (100) and the Hi-Reff facilities at the National Metrology Institute of Japan (NMIJ) (101) can reach Reynolds numbers above 10^7, a factor of ten higher than other facilities. The smooth pipe friction factors measured in these facilities differed by 6% at Reynolds numbers of 10^7. The Superpipe friction factors were 3% above the Prandtl smooth pipe friction line and NMIJ 3% below. Smooth pipe friction factors are among the few fluid dynamics factors accurately reproduced. The difference in the friction factors between the two facilities is so significant that it is highly likely that measurement errors are involved. Wall shear stress values, derived from fiction measurements, are used in turbulence studies. The causes of friction factor disagreement must be identified.

Researchers have queried the Superpipe results. Owing to improvements in the understanding of measurement limitations, several corrections have been applied to superpipe data. The Superpipe results have generally been vindicated. However, data sources against which to validate Superpipe data are required. Experiments to measure pipe friction factors at NMIJ were conducted by researchers using world-class facilities capable of high-accuracy flow measurement. Both facilities are closed-loop, but the NMIJ facility can divert its water flow to a weight tank to measure the flow rate. The Superpipe operates at air pressures up to 220 bar. The high-pressure pipework, in which a test pipe is located, has a side branch in which the measurement equipment is located, including a velocity traverse system that can scan 75% of a test pipe at a single traverse location. For the reasons below, the author queries the Superpipe mean velocity results that others do not. The author is an interested bystander regarding turbulence research, but what is involved here are assumptions about mean values, not turbulence properties.

D.1 Fully developed pipe flow - a concept, not a fact?

Numerous researchers have published experimental and DNS studies on VLSM. However, it remains unknown whether long-lived VLSM structures in turbulent pipe flow rule out a defined mean flow and turbulence environment at a particular location along a pipe which can be justified as fully developed pipe flow. In (17), “It was found that large-scale structures were continuing to grow in size past the points earlier thought to be fully developed. As the large-scale structures require a longer development length, it is proposed that the main criteria for a fully-developed pipe flow should focus on the development of these structures rather than on the mean velocity profile or higher order statistics”. It took approximately 180 pipe diameters from the inlet before the tendency to develop longer structures ceased. How the structures in a cross-section continue to change is unknown. As are the effects of the Reynolds number on the form and length of VLSM. In The Review (8), a comment on VLSMs, "One key question concerns their scaling. If they depend on the scale of the apparatus, it suggests the disturbing and profound possibility that it is not possible to realize a facility-independent asymptotic state of turbulence (even for fully developed internal flows, such as pipes and channels)”. Several researchers report that DNS studies have indicated that VLSM can extract energy from the mean flow; however, the extent to which this affects their persistence is unknown.

The concept of a fully developed flow was used in Superpipe studies to justify a velocity traverse at one location across 75% of the pipe diameter to calculate the flow rate. Averaged over a measurement period, sufficiently high and low energy large-scale motions should pass through a point at a given radius to provide an average velocity reading at that radius. If VLSMs are organised to some extent and persist in a particular pattern for an extended time, flow rate prediction from a single velocity traverse will not provide an accurate flow rate. DNS results in video form looking along a pipe show regions of low energy fluid penetrating towards the centreline with uneven distributions around the pipe circumference (102). However, the reasons for this uneven distribution have not been explained.

Researchers at NMJI conducted laser Doppler velocimetry (LDV) surveys in a pipe with a diameter of 100 mm. Twenty-four traverses to the centreline, with ten points per traverse plus the centreline. A total of 241 measuring points. A plot of the velocity contours (103) shows contours distorted around the centreline. A study in the proceedings of the Royal Society in 1932 described measurements using an ultramicroscope to view the movement of sub-micron particles in turbulent flow in a pipe (104). One of the observations was that fluctuations as high as 20 per cent of the mean flow rate occurred along the pipe axis. DNS simulations such as (104) report that low-energy VLSM occasionally extends from the logarithmic layer to the centre of a pipe; this phenomenon may have been observed in the ultramicroscope study.

More recently, researchers at NMIJ carried out LVD measurements on a 387 mm diameter pipe (105). It was noted that the velocity profile was completely axisymmetric, and integration of the velocity profile provided a flow rate within less than 0.6% of the gravimetric method.

A study of integration techniques for velocity traverse methods of flow measurement (106) found that an accuracy of 0.2% could be expected from eight equally spaced traverses to the centreline with five points per traverse plus the centreline and with knowledge of the theoretical velocity distribution used in the integration method.

Researchers observing flow with an ultramicroscope pointed out that von Karman’s constant in the logarithmic law that describes the longitudinal velocity in turbulent boundary layers was invalidated because it required zero fluctuations on the centreline (103). As turbulence fluctuations on the centreline are very short-lived, this should not invalidate the use of the von Karman constant.

D.2 Superpipe and NMIJ pipe roughness

A possible reason for the difference in the Superpipe and NMIJ friction factors is the Superpipe wall roughness. The roughness height and form may have caused the friction factors to increase above the hydrodynamically smooth wall friction factors. Several researchers have argued that Superpipes’ roughness affected friction factors, but no argument has prevailed.

The roughness of the 129 mm diameter aluminium Superpipe was initially established as 0.15µm by three assessors against a comparator plate (100). Later, surface stylus and optical imaging (107) confirmed the surface roughness but also revealed a surface wavelength of 10 µm, characteristic of a honing process. The honing groves were more or less at right angles to the flow direction. The medium used to achieve the final surface finish was Scotch-Brite©, very fine pads. The manufacturer quotes an expected 0.20-0.30 µm finish for aluminium, probably based on random polishing action not honing from a rotational motion with a slow axial movement that produced the Superpipe finish. In the report on the Superpipe facility (100), the comment is made “When looking at a surface with a 6µ inch (0.15 µm) rms finish, a written symbol can be distinguished in the reflection up to a distance, between the surface and symbol, of approximately 1 inch". This can be considered a dull mirror finish.

The NMJI surface finish on stainless steel is quoted as Ra = 0.10 µm for a 100 mm pipe and 0.25 µm Ra for a 387 mm pipe. The PowerPoint presentation (101) of the NMIJ facilities includes a photograph of a toy figure standing in a polished pipe. The figure's reflection around the pipe could be described as that of a bright mirror surface. The author’s reaction on first seeing the NMJI photograph was that it had the characteristics of an electropolished surface, but this was not the case. The contractor achieved the finish using a proprietary polishing process, which the contractor is unwilling to disclose (108).

Observations in (100) included the effects of changes in the Superpipe roughness at a considerable distance upstream of the velocity traverse location. The initial superpipe tests revealed that the pipe as received was not hydrodynamically smooth. The final 54 pipe diameters were re-polished to the estimated 0.15 µm, and lower friction factors were measured. For unspecified reasons, a decision was made to polish the remainder of the pipe to a surface finish of 0.15 µm. Polishing the pipe 54 diameters upstream of the velocity measuring location reduced the friction factors and changed the velocity profile relative to when only the last 54 diameters were re-polished. The friction gradient was measured using static pressure tappings from 32 diameters upstream of the main measuring section. Therefore, before the final re-polishing, there was a 22-diameter section of re-polished pipe before the first static pressure tapping used to measure the friction gradient. Studies of the effect of a change in surface roughness, such as (110), show that a 22-diameter distance between the change in roughness is sufficient for a developed friction gradient in the downstream pipe. However, the velocity profile 54 diameters downstream of a change in roughness could still be developing because of the need for the disturbance in a change in roughness to propagate towards the centreline and back towards the wall. The changed Superpipe velocity profile may have resulted in an apparent change in the flow rate leading to a lower friction factor being derived.

The effect of a change in pipe wall roughness raises a question regarding the NMIJ's larger diameter pipe for experiments that reached the highest Reynolds numbers. The 387 mm diameter pipe had a polished length of 31 pipe diameters, preceded by 36.7 dimeters of unpolished pipe. However, studies of change in wall roughness, such as (110), indicate a sufficient length of polished pipe before the static pressure tappings to accurately determine the friction gradient. In a more recent study involving LVD measurements, the roughness of the 100 mm diameter pipe is given as 0.8 µm, an Rz measurement of the vertical distance from the highest peak to the lowest valley (111). For LVD measurements on the 387 mm diameter pipe (112) at Reynolds numbers up to 3.1×10^6, the polished pipe length was increased to 55 diameters and the unpolished to 40 diameters. The mean surface roughness of the polished pipe was 0. 2 µm, and the maximum roughness was 1.7 µm. It should be noted that in (111), the experimental arrangement shows that the water flowed directly from a header tank. This is an ideal arrangement because there are no pump-induced fluctuation sources.

At a Reynolds number of approximately 0.3×10^6, the Superpipe friction factors began to rise slowly above the Prandtl friction line and by 3.5×10^7 was 3% above the line. Several studies have indicated that smooth pipe friction factors begin to fall below the Prandtl smooth pipe friction factor curve before Reynolds numbers of 10^6. These studies include the DNS simulation (112) and friction factors from the commissioning of the Cottbus Large Pipe (CoLaPipe) facility at the University of Brandenburg (113) and the (CICLoPE) facility of the University of Bologna (82). The author is concerned about these two commissioning studies as both facilities do not have adequate flow measurement capabilities. It's as if they were designed as wind tunnels which rely on calibration during commissioning but without the means for calibration. A flow metering installation with a target accuracy of 0.1 to 0.2% is possibly required for the facilities to generate accurate fluid dynamic parameters. Integration of 8 or more wall-to-centreline velocity traverses could be used to calibrate the inlet contraction to the test pipes.

The CoLaPipe commissioning study used inferred methods for non-dimensionalizing parameters, which is unacceptable for a research facility. CICLoPE assumed a discharge factor of unity for its inlet contraction and calculated the flow rate based on the static pressure difference across a 4:1 area ratio contraction. A Prandtl tube was installed at the outlet of the contraction, and a discharge coefficient of unity was assumed for the contraction. This assumption is not supported by velocity traverses which show a significant boundary layer at the contraction outlet. No details were provided on how the tappings for flow metering were checked.

A final comment relates to the von Karman constant *k*, which is a disputed flow parameter. NMIJ researchers (111) determined a value of *k* = 0.386 based on friction and velocity profile measurements. They compared their value with recent values of 0.384 and 0.387 for channel flows and 0.384 for zero pressure boundary layers. The best estimate for the atmospheric boundary layer is 0.387±0.010 (114), and Superpipe *k* = 0.4±0.02 (115). The Superpipe value is a revision from *k* =0.421, given in (100). The convergence towards common values for pipe, channel, zero pressure gradient and atmospheric boundary layers needs to be confirmed by further studies.

D. 3 Conclusion on friction factor differences

1. How the Superpipe friction factors departed from the Prandtl line is not typical of the generally expected inflexion curve departure due to roughness.
2. The NMJI friction factors dropping below the Prandtl smooth pipe curve are consistent with other measurements of smooth pipe friction factors showing that the Prandtl curve begins to overpredict friction factors before a Reynolds number of 10^6.
3. The departure of the Superpipe friction factors above the Prandtl smooth pipe curve before Reynolds numbers of 10^6 indicate either unknown effects of roughness, flow measurement errors, or a combination of both.
4. A vast investment in intellectual talent and research funds repeatedly demonstrates that researchers need access to facilities and measurement technology to reveal the subtle effects necessary to understand turbulent boundary layers.

D.4 Comment on access to high-accuracy fluid dynamic research facilities

A PhD student supported by others carried out a remarkable project in building and commissioning the Superpipe facility for $250,000 (1995). If the facility were designed and built by a National Physical Measurement Laboratory, it would have a higher cost. However, it is unlikely that they would build it without a calibrated flow metering capability. The number of citations for papers related to Superpipe exceeded 1000 several years ago. If only 20% of the projects that cited Superpipe relied on results from the facility, a hundred times the budget for Superpipe could be involved in studies whose results are in doubt.

The importance of the Superpipe in global boundary layer research is a justifiable reason for retrofitting it with a full-bore high-pressure gas flow meter calibrated by a Fluid Metrology Group. Details have been published about the challenging task of providing the Superpipe with a stereoscopic particle image velocity (PIV) measuring capability (116). However, this will provide measurements along a single traverse line.

Smits, the advisor to the PhD student responsible for commissioning the Superpipe, in his 2022 Batchelor Prize lecture (117), commented, “I consider how recent advances have helped to answer some key questions on how turbulent wall-bounded flow develops with Reynolds number. This quest naturally prioritizes studies at high Reynolds number so that scaling trends can be identified, and there is always an underlying need for accuracy since we know from experience that such variations are subtle". Numerous fluid dynamics phenomena involve subtle effects. Not being able to measure these effects to indisputable values gives rise to competing interpretations of phenomena, leading to more studies, and the cycle continues. The only way to arrest the cycle is to make measurements of sufficient quality to quantify subtle fluid flow phenomena accurately. Facilities operated by national flow metering or other standards laboratories are probably required for such measurements.

The Hi-Reff facility is an example of a national flow metering facility adapted to conduct fluid dynamics parameter studies. There is a need for an international group of stakeholders to be involved in research studies and to campaign for researchers to have access to facilities to determine fluid dynamic parameters to agreed accuracies. There is still a need for innovative experimental turbulent boundary layer facilities at universities to achieve a deeper understanding of turbulent wall-bounded flow.

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