Icons of CFD

Professor Brian Launder

Turbulence and its mathematical modelling are of fundamental importance in industrial CFD. So, it is essential that the engineer, whether undergraduate or trainee, understands at least a little of the subject. However, it can be difficult to grasp. Nevertheless, a great teacher can overcome obstacles to understanding. Professor Brian Launder's lectures, talks and presentations on the mathematical modelling of turbulence have done that, and more; they have also inspired countless students to study and contribute to the subject. We may ask: from where does this ability stem?

Many readers will have heard of the k-**ε** model of turbulence (about which more later) and will associate the name 'Launder' with this and many other more sophisticated turbulence models. Yet, it is not widely known that Brian Launder's initial training following graduation at the head of his class in Mechanical Engineering at Imperial College, London, in 1961, was in experimental fluid mechanics. Both his Master's and Doctoral degrees (1965) were obtained for one of the earliest experimental studies on the effects of strong acceleration on turbulent boundary layers. Briefly, if the acceleration is sufficiently strong, the turbulent boundary layer can become laminar, leading to large reductions in rates of heat transfer. This phenomenon is known as laminarization and is of substantial importance in the flow over turbine blades. Indeed, Launder's postgraduate studies were undertaken in the Gas Turbine Laboratory at the Massachusetts Institute of Technology.

In fact, throughout his career he has continued with experimental research. As just one example, he led the development of a rotating test facility that reproduces the flow and thermal behaviour relevant to the internal cooling of gas turbine blades, for essentially engine conditions, producing data for turbulence model development and testing.

Launder (2015) writes:

"I've always seen experiment and modelling proceeding hand in hand. While my papers on modelling have been the most widely cited, certainly the experimental ones have given me insight and also provided the data bases for testing modelling ideas."

This synthesis of modelling and experiment means that Prof. Launder has a deep insight into the behaviour of turbulence, which he can readily communicate. It has provided the foundations for his ideas on modelling.

Launder returned from MIT to Imperial College, London, in 1964, first as Lecturer, and later Reader in Fluid Mechanics, where he remained until 1976. This was a period of remarkable research and growth in CFD, and this was nowhere more evident than at Imperial College, under the direction of Prof. Brian Spalding – whom we met in a previous issue of Benchmark. Spalding's research group was tackling many of the key issues necessary for engineering CFD to become a reality. A vital aspect of this research was the development of turbulence models suitable for industrial applications; it was Launder who led this work.

By the late 1960s, with his first PhD student, Kemal Hanjalić, Launder had built on earlier developments to devise a practical turbulence model for wall-bounded and free flows. This model was extended by Bill Jones, also a PhD student of Launder, to be applicable right down to the wall, and was successfully applied to model the laminarization of turbulent boundary layers. Publishing their research as Jones and Launder (1972), this model became the workhorse of industrial CFD; it is the k-ε model of turbulence. As they wrote in the abstract to this paper:

"The paper presents a new model of turbulence in which the local turbulent viscosity is determined from the solution of a transport equation for the turbulence kinetic energy and the energy dissipation rate."

This was accompanied by extensive testing of the model against a wide range of experimental data, and fine-tuning of model constants (Launder et al., 1972), resulting in the Launder and Spalding (1972) book, and culminating in the widely cited paper of Launder and Spalding (1974) which defined what we today refer to as the 'standard' k-ε model.

This approach to the modelling of turbulence is based on the sweeping assumption that the effects of turbulence are, in a limited sense, broadly equivalent to an enhancement of the fluid viscosity; the so-called eddy-viscosity concept. Dimensional analysis shows that an eddy viscosity can be calculated, provided that a velocity and length scale can be found which are characteristic of the large-scale turbulent motion. Two transport equations (i.e. differential equations) are solved to obtain the turbulent velocity and length scales at each location in the flow; that is why this class of models is often referred to as two-equation models of turbulence.

The velocity scale is determined by solving a transport equation for turbulent kinetic energy, k, and taking its square root to give a velocity scale of $k^{1/2}$. Launder and his co-workers (unlike Spalding and his students) chose the dissipation rate of turbulent kinetic energy, ε, as the dependent variable of the second transport equation. This was an appropriate variable to define the length scale of the large turbulent motions because energy cascades from the large scales down towards the smallest dissipative motions. Dimensional analysis then gives the turbulent length scale as $k^{3/2}/\varepsilon$.

Almost all CFD software in use today for industrial applications will include the k-ε turbulence model or a variant thereof. It remains very widely used. However, that scheme and, more generally, two-equation eddy-viscosity models are known to have significant limitations and weaknesses. This was recognised at the outset by Launder and his students, even as they were developing and testing the k-ε model. For instance, turbulent flows in which the streamlines are highly curved (many flows of interest!), or are impinging (such as a jet impacting on a surface), or highly swirling (as in a cyclone separator), are usually poorly-predicted by two-equation eddy-viscosity models. These can be classed as flows with complex strain fields. In addition, flows in which body forces act to modify turbulence, as in many rotating or buoyancy-dominated flows, are also potentially poorly-predicted by such two-equation models.

Why is this? Essentially, the eddy viscosity concept relies on an assumed algebraic relationship between the effective turbulent fluxes of momentum (known as the Reynolds stresses, after Osborne Reynolds' work in Manchester in the latter part of the 19th Century) and the strain field which creates and sustains turbulence. In the standard k-ε model the Reynolds stresses are assumed to be linearly proportional to strain rates. Unfortunately, this proves to be an unsound approximation for many flows, as already highlighted. Launder worked with Hanjalić and post-doc Wolfgang Rodi among others to develop a fundamentally different approach to the modelling of turbulence (Launder et al., 1975):

"....in which the Reynolds stresses are determined from a solution of transport equations for these variables and for the turbulence energy dissipation rate, ε."

In this approach, the eddy viscosity makes no appearance, and instead the six Reynolds stresses (three shear and three normal stresses) are found from the solution of their own transport equations, making a total of seven transport equations (including an ε-equation). This is known as the Reynolds-Stress-Transport Model approach or, more generally, as Second-Moment Closure, i.e. when extended to the modelling of turbulent fluxes of heat and chemical species.

One of the main advantages of second-moment closure is that the terms which represent the generation of Reynolds stresses are represented exactly in their respective transport equations. Of course, other terms in these equations must be approximated, and when compared to two-equation models there are now seven transport equations to solve - requiring more computational effort. However, this approach can potentially lead to the capture of far more complex flows and phenomena than is possible with a two-equation model.

In 1976, Launder went to the University of California, Davis, as Professor of Mechanical Engineering. After developing the Split-Spectrum model* with Hanjalić and French post-doc Roland Schiestel (Hanjalić et al. 1980) in 1980 he returned to the UK as head of Thermo-Fluids at the University of Manchester Institute of Science of Technology, UMIST (since 2004 part of the University of Manchester). His research remained focused on the development and testing of engineering turbulence models, often in collaboration with industry. He extended second-moment closure models to better account for the effects of walls, in particular their effects on turbulent heat transfer, working with two outstanding research students who stayed on as academic colleagues, Prof. Hector Iacovides and Dr Tim Craft.

*** In the Split Spectrum approach, the turbulence energy spectrum is divided into two parts: a 'production' region and a 'transfer' region. The turbulent kinetic energy is fed into the production region from the mean flow and moved into the transfer region where it is dissipated, to model the effects of the energy cascade from larger to smaller scales.**

This research addressed ever more complex flows, both physically – due to complex strain fields and/or body forces - and geometrically. Two key papers covering much of this work are Iacovides et al. (1996) and Craft et al. (1996a). To his regret, however (partly due to its algebraic complexity), this two-component-limit† (TCL) closure is used in CFD much less than his early model (Launder et al.,1975) in spite of it being far superior in accuracy and range of applicability. However, a simpler model from that time – indeed, the first cubic non-linear eddy viscosity model, Craft et al. (1996b), is widely cited and used. In this approach the Reynolds stresses are obtained from a more general non-linear function of strain rate and vorticity, and in its cubic form this results in a model which can show sensitivity to streamline curvature, impingement, swirl and rotational effects.

A further area where he has productively collaborated with his two colleagues, Craft and Iacovides, is in developing wall functions. These are simpler treatments that effectively provide a linkage between the velocity at the node in the near-wall, fully-turbulent region to the wall shear stress (thus avoiding the need to carry the full CFD computation through the viscosity affected near-wall sublayer). The most common such scheme is the so-called 'law of the wall' which, alas, only accurately applies in far simpler flows than one habitually has to deal with in CFD. Two new schemes were thus developed, one algebraic (Craft et al., 2002) and one numerical (Craft et al., 2004) that have been shown to achieve far wider applicability. Much of the research from this Manchester period is summarised in a book, co-authored with his first doctoral graduate, Hanjalić & Launder (2011).

In 1994 Launder was elected a Fellow of both the Royal Society, and the Royal Academy of Engineering, in recognition of his contributions to the modelling and measurement of turbulent flows. He has also received honorary degrees from four universities and many other international honours.

Over the last two decades his research has widened considerably to include environmental concerns, and from 2000 to 2006 he was Regional Director of the Tyndall Centre for Climate Change Research. In 2004 he attended a conference on climate engineering ('geo-engineering') at Cambridge and was persuaded that it needed further urgent investigation. He has repeatedly argued, to parliamentary committees and elsewhere, the case for research funding in this area so that, if catastrophic climate change becomes imminent, such techniques may potentially be in a state of readiness. In 2008-09 he served as the only engineer on the committee producing the Royal Society's (2009) position statement on geoengineering climate change and in the following year co-edited a book on the same theme, Launder & Thompson (2010).

In conclusion, Prof. Brian Launder has been instrumental in the development of practical engineering turbulence models, from the earliest days of industrial CFD to the present. These models, or their variants, can be found in most CFD software which is currently commercially-available, attesting to the impact of his work. Many of the PhD students with whom he has worked in developing and testing these models have themselves gone on to make very significant contributions to engineering CFD, whether as university professors, leaders in industry or national research institutions. Launder is truly an 'Icon of CFD'.

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† For instance, the two-component limit is approached at a wall (or other interface, such as a liquid surface), as the turbulent velocity fluctuations in the direction normal to the wall or interface must vanish more rapidly than those parallel to the wall/interface.

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