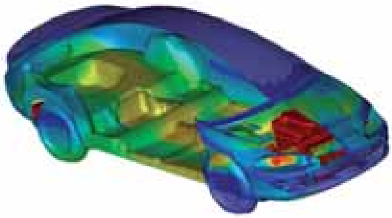
# icons of CFD



In this new series of articles, Chris Lea profiles some of the leading lights of the CFD world.

## Professor Brian Spalding

The decade from the mid 1960s to the 1970s was a time of rapid technological development, highlighted by the achievements of the Apollo space programme. At the beginning of this period Computational Fluid Dynamics was in its infancy; in fact the terminology "CFD" hadn't yet been coined. It is true that research on numerical methods for fluid flows, models for turbulence, and the like, was underway – for instance at the Los Alamos National Laboratory. But much effort and development was still needed to build upon this early research if a wide-range of engineering fluid flow problems were to be simulated. That these efforts were made, and were successful, is evident by the CFD tools at our disposal today.

Where were these efforts made? Who had the insight and leadership to drive forward their early development for the purpose of engineering flow simulations?

It is no exaggeration to say that Professor Brian Spalding is the father of engineering CFD. By the late 1960's, he was leading a CFD group of more than 30 researchers at Imperial College, London, as Professor of Heat Transfer. This group was tackling some of the key issues necessary for engineering CFD to become a reality, such as the development of flow solvers, numerical discretisation techniques, practical models for turbulence, etc.

Let us examine Prof. Spalding and his Imperial College co-worker's contribution to just one of these issues: turbulence. The need for practical and reliable models for turbulence was paramount in the late 1960s/early 1970s, and in fact has not diminished since that time. This is because many engineering flows are turbulent, and turbulence greatly affects rate of heat, mass and momentum transfer, as well as chemical reaction. Unfortunately, it is not possible to simulate turbulence directly – except for some very simple flows, as the ranges of length and time-scales of turbulent motion are so large that the required computing resources rapidly become impractical. Instead, a model for turbulence is required.

One approach to the modelling of turbulence is based on the assumption that the effects of turbulent flow are, in a limited sense, broadly equivalent to an enhancement of the fluid viscosity; the so-called eddy-viscosity approach. 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. Now, in the late 1960s/early 1970s a range of methods to obtain these velocity and length scales were being explored, by a handful of research groups. The velocity scale was most often determined by solving a differential equation for turbulent kinetic energy, k. In the simplest approaches the length scale was prescribed, typically by calibration. Here is what Spalding had to say about such an approach, during a questions and answers session at a conference hosted by the NASA Langley Research Centre in 1972:

*"I would just like to say that it is our opinion that if one is interested in flows of any generality at all, one can forget about formally prescribing the length scale. The only practical way forward is to deduce the length scale by solving an appropriate differential equation. We need to think of only simple separated flows like the flow downstream of a sudden enlargement in a pipe and we immediately see that the length*

*scale just downstream of the enlargement and in the neighbourhood of it must be similar to that in a mixing layer, because there is a mixing layer there. Far downstream the length-scale distribution of a pipe flow must be approached. Then, in the eddy region, there is some kind of length scale which perhaps close to the wall is proportional to distance. You can see the limits but you can't tell at all how to propose the length-scale distribution. I think it is not worthwhile. If you can solve any differential equations at all, you can solve those two extra ones – one for the energy and the other for an equation which will lead to the length scale. I would argue that's what all engineers ought to do".*

This reply very clearly sets out the case for the length scale to be calculated by solving a differential equation. Work by Spalding, Launder and other researchers at Imperial College, in which differing forms of length-scale equation were tested, led to their adoption of the dissipation rate of turbulent kinetic energy, $\varepsilon$, as the preferred second differential equation. Somewhat as an aside: the length scale is then given by $k^{3/2}/\varepsilon$, by dimensional analysis, and Â is an appropriate turbulence quantity to define the length scale of the large turbulent motions because energy cascades from the large scales down towards the smallest dissipative motions. The Imperial College research group also carried out numerous calculations in which they calibrated the 'constants' in the model so that they provided a best fit to a wide range of simple shear flows – such as jets, wakes, mixing layers, etc.

The end result of this research effort was the well-known $k$-$\varepsilon$ turbulence model, reviewed in Launder and Spalding (1974). This work established turbulence modelling as a practical and viable technique. Although the $k$-$\varepsilon$ model is known to have a number of limitations and weaknesses, it is still very widely used; almost all engineering CFD software in use today will include this model – amongst others.

In his very early career, Spalding worked for Shell before joining the Rocket Propulsion Establishment in the Ministry of Aircraft – set-up to develop rocket technology. He subsequently worked for the National Physical Laboratory, before obtaining his PhD from Cambridge University – on the combustion of liquid fuels. He stayed at Cambridge for a short time undertaking further research on combustion, before joining Imperial College in 1954 as a Reader, gaining his first Chair in 1958. No doubt this early career influenced his later contributions to the CFD modelling of combustion.

In the field of combustion, Spalding (1971) developed the eddy break-up model for premixed reactants, later extended to non-premixed flows. This model is based on the premise that in a turbulent flow in which the chemistry is very fast, the rate of chemical reaction is essentially governed by the rate at which reactants mix with hot combustion products. The reaction rate is then assumed proportional to a turbulent time-scale. This time-scale can be found in a similar manner to the length scale above, by dimensional reasoning. This model has provided engineering solutions for many combusting flows. Even though it has been superseded by more sophisticated models, including his own 'multi-fluid model', the eddy break-up model and its variants are nevertheless still in widespread use.

Spalding and co-workers at Imperial College also made seminal contributions in the development of practical numerical discretisation methods, and robust flow solvers. The 'SIMPLE' algorithm, developed by Patankar and Spalding (1972), has been the default flow solver (in one form or another) in most CFD software until recent times, and, like the $k$-$\varepsilon$, and eddy break-up model, is still widely used. The "upwind differencing" method was also developed by Spalding, using an intuitively-based "tank-and-tube" concept. In this method the fluxes associated with convection terms in the governing partial differential equations are obtained by extrapolating from the upstream direction only. In essence, this numerical discretisation scheme can be viewed rather like the one-way flow through a series of tanks connected by tubes. The tanks represent the control volumes or mesh cells, whilst the tubes represent the boundaries between cells through which the flow must pass. At the time, this was significant break through, for without it the group were confined to the modelling of low Reynolds number flows, whilst of course many engineering flows are at high Reynolds number. Further achievements of Prof. Spalding and the Imperial College group are covered by Runchal (2008).

The faculty staff and researchers who worked for and with Prof. Spalding in the Imperial College group reads like a Who's Who of CFD. This includes, in no particular order; Jim Whitelaw, Brian Launder, Suhas Patankar, Wolfgang Rodi, Kemo Hanjalic, Akshai Runchal, Micha Wolfshtein, Bill Jones and David Gosman. No doubt there were differences of opinion from time to time between such luminaries, as well as a creative dynamics. You may recognise some of these names, either those who now lead key research groups in academia, or have set-up and run successful CFD companies. In both cases, they have stayed engaged in engineering CFD; perhaps to some extent this reflects the influence of Prof. Spalding.

It should be no surprise to learn that the first commercial CFD services were set-up by Prof. Spalding, via the company of which he remains Managing Director – Concentration Heat and Momentum (CHAM) Ltd. He is the creator of the PHOENICS software, which appeared in 1981. However, it may be surprising to know that CHAM was incorporated and active as early as 1969. Indeed, until the early 1980's CHAM was the only consulting company offering commercial services in CFD. Spalding stayed at Imperial College until 1988, before giving his full attention to CHAM and the development of PHOENICS.

Prof. Spalding's contributions to CFD are underlined by his many publications and awards. Amongst the latter are the 2010 Benjamin Franklin Medal for Mechanical Engineering. In 2009 he received a Global Energy International award from the Russian President, Dmitry Medvedev. He is a Fellow of the Royal Society and Foreign Member of the Russian Academy of Sciences.

In conclusion, Prof. Spalding has been instrumental in bridging the gap between the underlying flow physics in industrial flows and the modelling techniques needed for their solution. In the 'Imperial College years' he had the insight to know which techniques were likely to work, as well as the drive to ensure that the CFD group's efforts were directed appropriately. When the way forward wasn't clear, he used physical reasoning to propose, develop, test and implement solutions. He is truly an 'Icon of CFD'.

Icons of CFD continues in the next issue of Benchmark, focusing on the early contributions and development of CFD from the United States, in particular from key NASA laboratories.

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Chris Lea spent Christmas and New Year relaxing at altitude, at home in Buxton.

His New Years Resolution is to get his 10 year old to teach him how to text, or SMS...