A Tribute to an Exceptional Life: **BRIAN SPALDING**

Dr. Akshai K. Runchal
Analytic & Computational Research, Inc.
CFD Virtual Reality Institute
runchal@gmail.com

CHT-17

May 29-June 1, Naples, Italy

An Exceptional Life

- **Brian Spalding made remarkable contributions to**
  - Combustion
  - Heat & Mass Transfer
  - Turbulence
  - Two-Phase Flows
  - Unification of Flow and Transfer Processes
  - CFD
  - <u>Global Heat and Mass transfer community</u>
  - <u>Commercialization of CFD Engineering Services</u>
- **Wrote 15 books and hundreds of publications**
  - Books on Combustion, Mass Transfer, Turbulence and CFD had a large impact on teaching and engineering practice.

Honors & Awards

- FRS (1983)
- FREng(1989)
- James Clayton Prize (1970)
- Max Jakob Award (1978)
- Medaille d'Or (1980)
- Bernard Lewis Medal (1982)
- The Luikov Medal (1986)
- Global Energy International Prize (2009)
- Benjamin Franklin Medal (2010)
- A. V. Luikov Prize (2010):
- Huw Edwards Award (2011)
- 75^{th} Anniversary Medal of the ASME HT Div (2013)
- Numerous other Honors and memberships

A Quick Review

- Born on 9th January 1923 in New Malden
- Died: 27th November 2016 in London
- Kings College School from 9 to 18
- Admitted to Air Force but wanted to become a RADAR operator, so joined Oxford University
- 1944 ➔ B.A. Eng Sci Oxford University
- 1945 ➔ RPE: Ministry of Aircraft Production
- 1948 ➔ M.A. Oxford
- 1952 ➔ Ph.D. Cambridge
- 1954-1988 ➔ Imperial College, London
- 1988-2016 ➔ CHAM

Context

- First met D. Brian Spalding in 1965 when he accepted me as his Ph. D. Student
  - The fact that I had an ICI scholarship for my Ph.D. – as had he – may have played a role
  - Later in life we talked of the coincidence that we were both selected for air force - neither joined
- Popularly known as DBS in IC circles
- Deep Brain Stimulation
  - My association with him was certainly DBS
  - And changed the course of my life

Phases of DBS Career

- 3 major phases to his professional career
  - Combustion
  - Unified Theory
  - CFD
- Made notable contributions to society
  - Brought Heat & Mass Transfer community together through journals and societies.
  - Led a campaign for freedom of soviet scientists
- Started the field of Commercial CFD
- A linguist – English, German, Russian & French
- Had a deep interest in Poetry
  - Translated Soviet poets
  - Wanted to be remembered as poet

Origin of Interest in Combustion

- **Joined RPE**
  - Set up in response to German V2 rockets
  - Had no rockets yet.

- **1945-1946: Germany**
  - Luftfahrtforschungsanstalt Herman Goering near Braunschweig
  - Worked with team that developed motor for Messerchmidt 163 rocket-propelled airplane
  - The propellants were hydrazine hydrate and H2O2. Highly unstable.
  - Set them to work converting to kerosene and LOx
  - In 1946 the team was transported to England
- **1948 → ICI Fellowship to Cambridge for a Ph.D. kin Liquid Fuels**

Remarkable Ph.D. in Combustion

- Ph.D. Thesis unified key concepts of:
  - Hydrodynamic: von Karman [1921]
  - Heat Transfer: Kruzhilin [1936]
  - Mass Transfer: Eckert [1949].
- Created a general theory of H & M T with & without combustion.
- Developed the B factor – Spalding Transfer Number
- Made a then unforeseen prediction that:
  - Rate constants have no influence on combustion until a critical rate of mass transfer is reached.
- Deduced critical rates by adapting the concepts of Zeldovich and Frank-Kamenetsky, and Semenov,
- Led to a general theory for prediction of flame-extinction - a breakthrough for combustion engineers

Other Contributions in Combustion

- Other notable contributions in combustion include:
  - A cooled porous burner for measuring flame speeds
    - Determining Adiabatic Flame speed by measuring non-adiabatic flame speeds
  - 'centroid rule' : a range of flame-speeds fall on a single curve
  - The cooled-liquid- film burner for measuring combustion rates
  - An innovative method for measuring extinction conditions
  - An electrical analogue of combustion - unique concept to my knowledge.
  - Eddy Break-Up model for turbulence-kinetics interactions
  - Multi-fluid model for turbulence- kinetics interactions

To Imperial College

- Recruited by Prof. Owen Saunders in 1954 to join as Reader in Applied Heat, in MED at the Imperial College, London.
- Spalding continued working in combustion
  - Key and innovative contributions in evaporation burning of droplets
  - Remarkable book on Heat and Mass transfer [1963] that has greatly influenced subsequent work in this field.

Unified Theory

- In late 1950s Spalding turned his attention to shear flows.
- The turbulent velocity profile for walls; a 3 part profile: “viscous”, “transitional” and “fully turbulent” layers.
- Found an unconventional and elegant solution: Y+(U+)
  - This enabled a continuous-function 'wall law'.
- Unified Theory of Turbulent Boundary Layers, Jets and Wakes.
  - His “grand” design to build on the insights of Taylor
  - A single theory for BL, Wakes and Jets.
  - Based on the remarkable insight of a “universal” entrainment law
  - A suitable two-part profile to represent the wall and wake regions
  - A number of students worked on UT [Escudier, Nicoll, Jayatillaka].

1964-1965 – Recap of UT

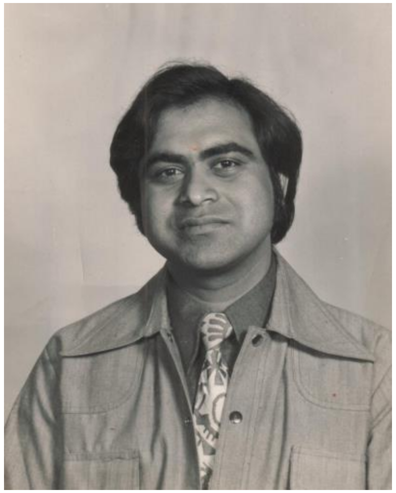
- The standard method to solve BL equations was "profile method" developed by Polhausen
  - This required a suitable profile that met flow constraints
  - This was problem specific and painful
- Brian concluded that profile can be "universalized" by representing it as a piece-wise polynomial
  - Freed one from the tyranny of having to find an "ideal" profile
  - Had already determined "optimal" entrainment functions, log-law constants and heat and mass transfer resistance required to describe a wide range of flows.
  - Worked with a series of students with fair success
- Patankar successfully
  - Developed a general "integral-profile" code
  - GENMIX

1965 – End of UT Dream

- **Spalding was confident that most flows of engineering interest can be represented by UT.**
- **Soon became apparent that search was not yet over**
  - **Generated solutions that were occasionally spurious or singular.**
- **Unified Theory also failed for flows with:**
  - **High stream-line curvature**
    - **Cavity Flows**
  - **Separated flows with adverse pressure gradients**
    - **Flow behind step in a pipe**
  - **Strong favorable pressure gradients**
    - **Impinging Wall jets**

Early CFD Phase: 1965-1969

- **Spalding started with 2-D steady state flows**
- **Stream-function (ψ) & vorticity (ω) as state variables**
- **Wolfshtein started with Impinging Wall Jets**
- **Runchal started with Square cavity & Pipe-Step**



Status of CFD in 1968 - Key Innovations

- 1966 saw the first success in using FD for separated flows and impinging wall jets
- For high Re flows Brian made an analogy
  - Wind from pigsty always stinks (He had grown up close to a pigsty)
  - Wind from the north always brings cold.
  - This led to Brian proposing the “upwind” concept.
- He also Introduced the concept of tanks (control volumes) connected by tubes (grid).
  - The formalization was later renamed “Finite Volume”
- T&T was a key breakthrough
  - Focus of interest is Fluxes not variables (velocities).
  - No Taylor’s Series; no basis functions
  - No equating “order” with ‘accuracy”.
- “Physical” rather than “mathematical” approach

“Birth” of CFD - 1969

- In 1969 Brian organized a Post-Experience Course at Imperial College
  - Targeted at both academic and industrial communities.
- The work done at IC, including the ANSWER code, became widely available through the book by Gosman et al., 1969.
- The computer code to solve generalized transport equations for any 2D flow was freely distributed
- It ushered in CFD as an engineering tool.
- Brian incorporated CHAM Ltd.
- Commercial services in CFD became available through CHAM.

Mature Phase of CFD – 1972
The SIMPLE Life

- By 1970 Brian became convinced that ψ-ω approach was not viable for 3D flows - he turned to primitive variables
- Harlow [1965] had introduced a staggered grid and a decoupled pressure for transient flow.
- Cholesky [1967] had pointed out that any scalar can be used in lieu of pressure.
- Patankar and Spalding [1967] had already used this approach for parabolic flows.
- Patankar and Spalding [1972] combined these insights into SIMPLE
  - It revolutionized the CFD practice.

Spalding & Turbulence

- Brian knew that CFD will not be a really useful unless it dealt with turbulence and chemical reactions.
- He built upon the work of Kolmogorov [1942], Prandtl [1945], Chou [1945] and Rotta [1951]
- He turned to getting the constants from experimental data with bold assumptions about their "universality" (or usefulness) .
- This led to the k, k-l and k-ω methods and later the EBU.
- Harlow and coworkers [1967] published the 1st paper on k-ε model
- Launder and Spalding "standardized" the k-ε method

CFD Post – 1975 Phase

- 1969 – 1981 Spalding led the largest CFD group in the world with more than 30 researchers
- 1988 Spalding left IC to devote full time to CHAM
- PHOENICS, 1st commercially available CFD tool, 1978.
- Brian went on to invent highly useful tools:
  - IPSA Algorithm for predicting multi-phase fluid flow
  - A simple algorithm to determine the wall distance
  - A multi-fluid approach to turbulence and turbulent combustion
  - A novel approach for integrated radiation computations
  - A methodology to unify fluid and solid mechanics

Harlow & Spalding

- Brian always had a great sense of humor. When I informed him that Harlow had died, he remarked – "he has upstaged me again".
- Harlow started almost a decade before Spalding - Los Alamos had computers a decade earlier
  - Many key CFD breakthroughs at Los Alamos
  - Primitive Variables, staggered grid, pressure decoupling
  - Eulerian and Lagrangian approaches
  - 2-Equation Turbulence models
- Harlow focus was on "science" than "engineering"
  - Steady state was viewed as asymptotic to transient
  - Expensive for practical engineering applications
  - No commercialization or dissemination of tools
- Primary focus of Spalding was "engineering" flows for industry.
- Spalding made his CFD technology widely available
  - Personal contacts
  - Post-experience courses
  - Free distribution of computer programs
  - Publication of books.

Synopsis - I

- **Brian did not invent the "science" of CFD but more than anyone else, *he created CFD as an Engineering Tool*.**
  - **Most of today's commercially available CFD tools trace their origin to the work done by Spalding and his group in the decade spanning 1965-1975.**
- **He made enduring contributions in combustion, turbulence, heat & mass transfer and CFD.**
- **Brian was the first to focus on turbulence energy and its role on wall heat transfer for separated flows.**
  - **Breakdown of Reynolds Analogy**
- **He was also first to formally propose that all 2nd order transport equations can be expressed and solved as a single generalized transport equation.**

Synopsis - II

- He had over 80 graduate students.
  - Many well-known names in CFD, turbulence or combustion today have a 1st or 2nd generation IC connection.
- He foresaw that unifying flow, heat and mass transport will lead to practical tools for engineers.
- He foresaw that CFD - once turned into to a design tool – would revolutionize engineering.
- His other work on turbulence, multi-phase, solid-fluid interaction and wall distance computation has not yet seen the same popular adaption as these but he has pointed to path-breaking research that may bear fruit in the future.

Farewell: D. Brian Spalding

- **You lived a remarkable life**
- **In Newton's words: *You stood on the shoulder of giants and saw farther than your peers*.**
- **You lived to Richard Feynman's Motto: Y*ou Did Not Care What Other People Think.***
- **You were so fond of re-phrasing Virgil: *You did what you did because you didn't know you could not*.**
- **Farewell my Mentor, my Friend and my intellectual Father**
- **You may not be with us but your legacy will survive for a long time to come**

We Remember