A lecture at the
International Symposium
HMT&H in Swirling Flow

Oct 21-23
Moscow 2008

Heat & mass transfer &
hydrodynamics in swirling flow

Enlarging the Frontiers of Computational Fluid Dynamics

by

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A lecture at the Third International Symposium HMT&H in Swirling Flow

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This lecture is a **shortened version** of my presentation at the 2008 International Computational Heat Transfer Conference in Marrakech.

I have added some **new material** about **swirling flows** for the present conference.

In the earlier lecture, I proposed **three directions** of CFD enlargement:

1, **stresses in solids**

2. **multi-phase flow**, and

3. The '**population dimension**', especially for combustion studies..

Today I add that it is **only** by way of 'fluid-population' studies that **swirling-flow hydrodynamics and heat transfer** will ever truly **become part of** Computational Fluid Dynamics

2. EXTENSION TO STRESS ANALYSIS
2.1 History

Before the electronic computer, analysts of **fluid- and heat-flow phenomena** on one hand, and **stresses in solids** on the other, used **similar** mathematical methods.

Analytical methods sufficed for only the **simplest** problems.

Therefore **numerical** methods were used, of **two kinds:**

1. 'presumed-profile', also called 'shape-function', using:

- parameterized expressions for the distributions of the solved-for variables (displacement, velocity, temperature, etc), **together with**
- approximate integral equations to determine their parameters, **and**

2. 'finite-difference', using algebraic equations connecting the values at a finite number of locations.

2. EXTENSION TO STRESS ANALYSIS
2.1 History (contd)

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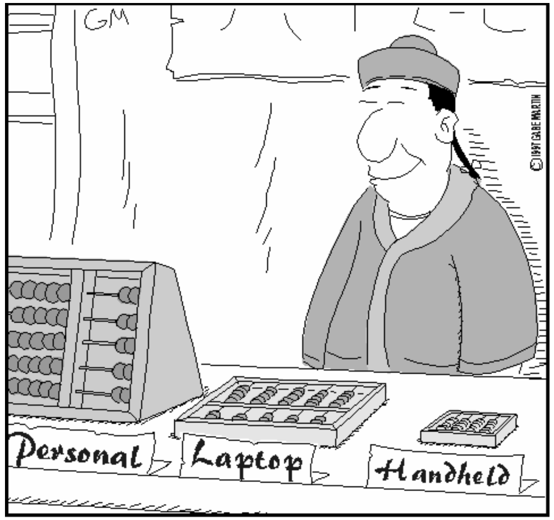
Equations of both kinds were **derived** from differential equations, embodying the underlying **physical laws**, by:

for **1**, multiplying the differential equations by a series of '**weighting functions**' and then **integrating** them **analytically** over the whole or parts of the domain **of interest**; and

for **2**, truncating a **Taylor-series** expansion.

The **presumed-profile** method **(1)** was often **preferred** because the **finite-difference (2)** method required too much **expensive human labour.**

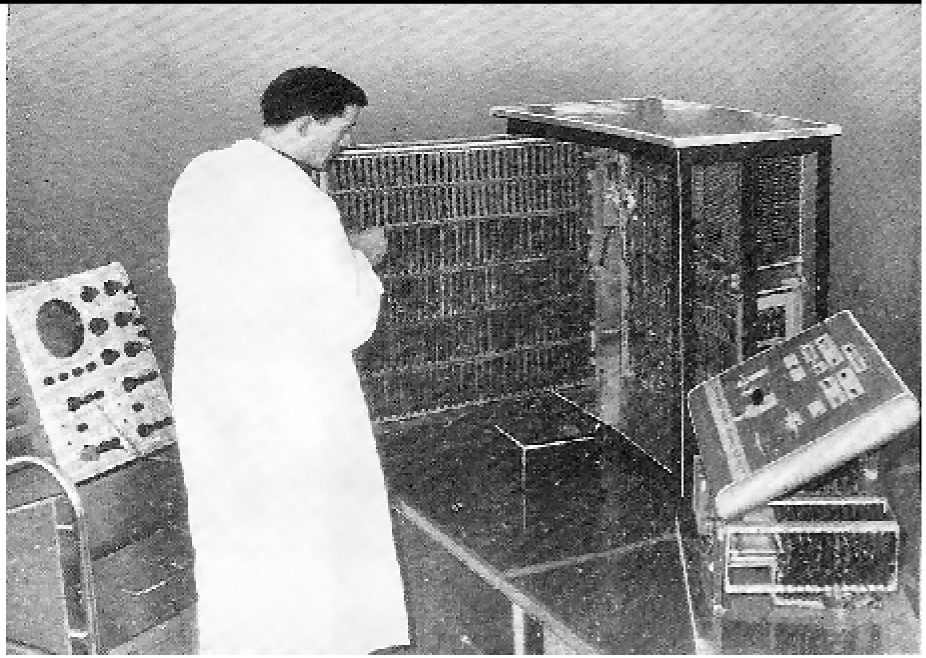


Ancient Computer Expos

2. EXTENSION TO STRESS ANALYSIS
2.1 History (contd)

The advent of the **electronic computer** set **'**human computers' free.

Yet the finite-difference method **(2) triumphed** immediately **only** for **heat conduction**.



Why?

Because a **single** differential equation was involved, whereas:

- **fluid-dynamicists** must solve **coupled** momentum and mass-conservation **equations**; and,
- **stress-analysts** must solve equations for displacements in several directions, **coupled by Poisson's ratio.**

2. EXTENSION TO STRESS ANALYSIS
2.1 History (contd)

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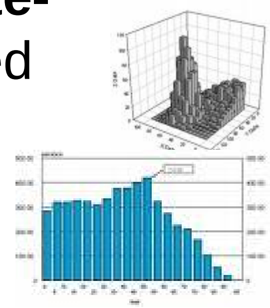
Fluid-dynamicists faced the **more severe** problem; for their equations have: **first-order derivatives**, representing **convection** fluxes; and varied **source terms;** and **turbulent transport**.

Therefore they soon agreed that it was best to solve **'finite-volume'** equations. These involved very simple 'presumed profiles‘ of **histogram** type; and they were derived by **integration** over contiguous 'control volumes‘, with a **'weighting function' of unity**, *i.e.* **no weighting at all.**



The stress-analysts also limited their integrations to contiguous control volumes, which they called **finite elements;** but they **retained non-unity weighting functions**.

This was the crucial **parting of the ways** between **UWFists** and **N-UWFists.**

2.2 Finite-volume & finite-element methods compared:

UWF *versus NUWF*

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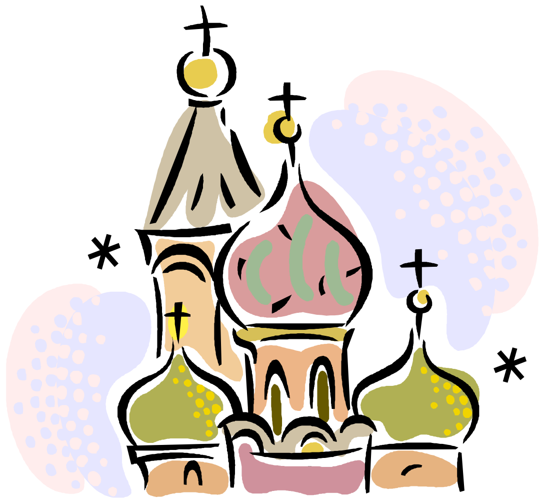
Concession 1: All fluid-dynamics problems **could be (and** many **have been)** solved with **non-unity** weighting functions, *i.e.* with finite-element methods.

Concession 2: Whatever weighting-function policy one adopts, the **same solution** should be arrived at to any particular problem, just as **Moscow is the same city** whether reached by **UWFist** (finite-volume**)** or **N-UWF**ist finite-element vehicles.



2.2 Finite-volume and finite-element methods compared
(contd)

Nevertheless I assert:

- The finite-volume method (henceforth **FVM**) **has** been used for solving solid-stress problems **by many authors** [Beale, Elias 1991; Spalding, 1993; Demirdzic, Muzaferija 1994; Bailey, Cross, Lai 1995 and more recently Artemov ], whether or not they **interact** with fluid- or heat-flow ones.

- Therefore the widely-held belief that the finite-element (henceforth **FEM**) **must** be used for solid-stress problems is **demonstrably false**.

- **This belief** has wrongly dissuaded the majority of stress-analysis researchers from paying any attention at all to FVM.

- Yet FVM is **inherently superior**, requiring only **one** function (that of the variable-distribution **shape**) to be guessed, not **two** (*i.e*. the **weighting** function in addition).

2.2 Finite-volume and finite-element methods compared
(contd)

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• The use of two functions by **NUWFists** has needlessly complicated the language and literature of FEM. It represent **needless baggage** carried in from pre-computer years, **with no advantage whatever.**.

• The **enormous and expensive effort** devoted to creating the finite-element literature represents a profligate and still-continuing **waste of resources**.

• Because solid-stress and fluid-flow analysts use **different methods,** engineers still **lack economical software tools** for solving fluid-structure-interaction problems.

• It is not too late to **change course**; and specialists in Computational Heat Transfer are well placed, by reason of their experience of FVM, to **take the lead**.

2.2 Finite-volume and finite-element methods compared: Some FVM-based results (end)

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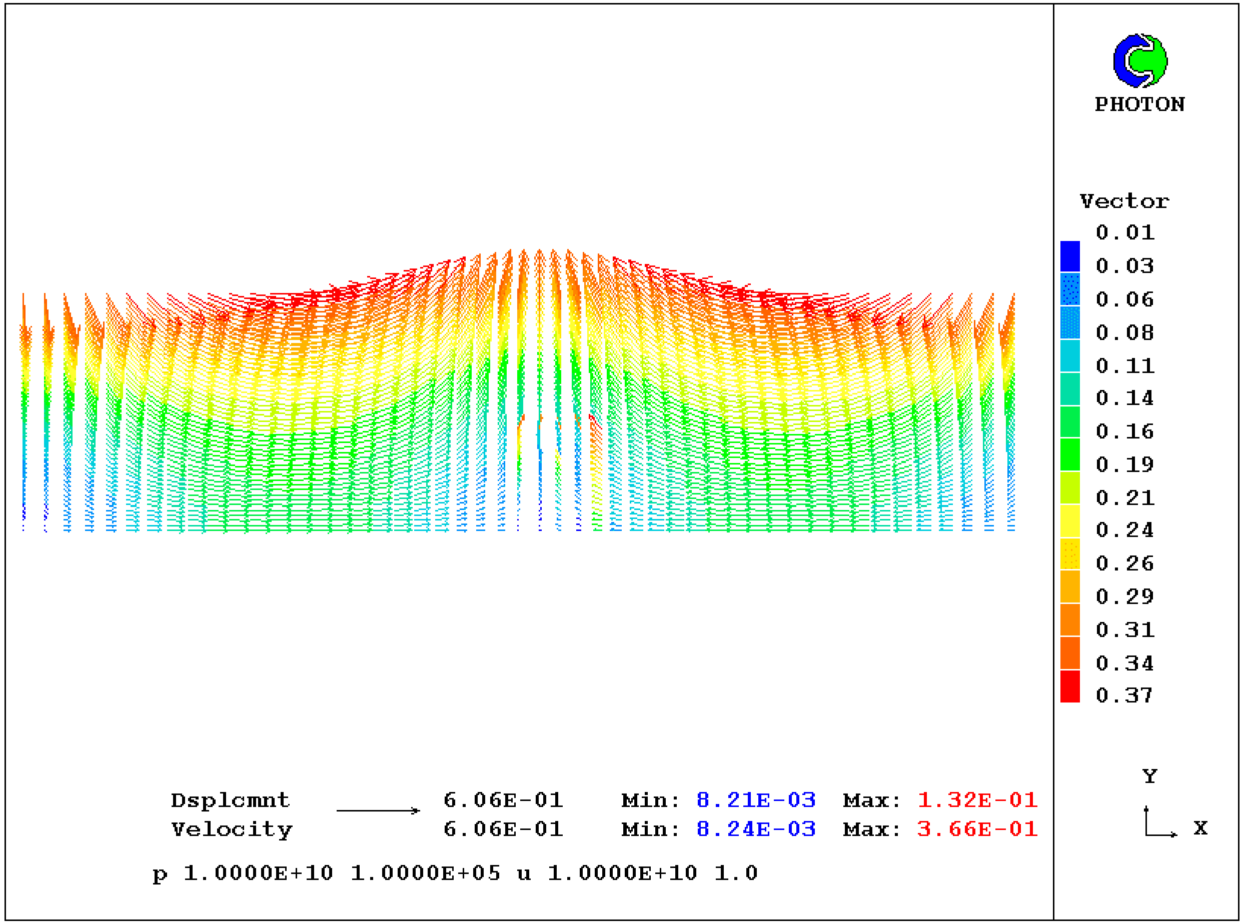
A final example: **deformation of an under-water structure** by periodic wave motion.



3. EXTENSION TO MULTI-PHASE FLOW
3.1 Overview

The phenomena in question.

Multi-phase-flow phenomena to which I urge CHT specialists to pay more attention are of two kinds: **free-surface** and **dispersed**.

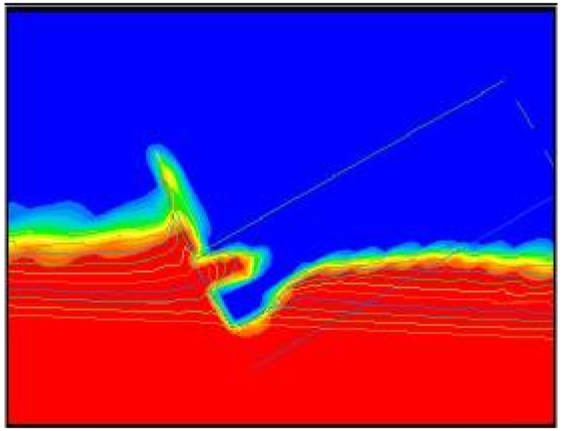
Examples of the **free-surface phenomena** include:

- **film condensation** of water from a steam-air mixture;
- **film boiling** at the surface of a hot solid immersed in a liquid;
- **vaporisation** and **burning** of a pool of oil;
- **melting of an icicle** in a warm wind;
- motion of **large vapour bubbles**, when **slug-flow** motion occurs in a tube.

3.3 Research opportunities in respect of free-surface flows

Research opportunities in respect of free-surface flows are also explained in the printed text. I merely **summarise** here:

- **Fitting the grid to the surface** is rarely practical; surface shapes are **too convoluted.** The motion must be defined by reference to a **pre-determined grid.**
- **A two-phase model** may be used; but numerical diffusion makes the surface fuzzy.
- **Particle tracking** is useful (seen on right); but algorithms vary greatly in efficiency.



- The **volume-of-fluid** scalar-equation method has many advocates, and variants. Improvements are still needed, *e.g.* for multiple layers.
- Another scalar-equation method, called **level-set,** can produce spectacular results seen on the next slide.

3.3 Research opportunities in respect of free-surface flows (end)

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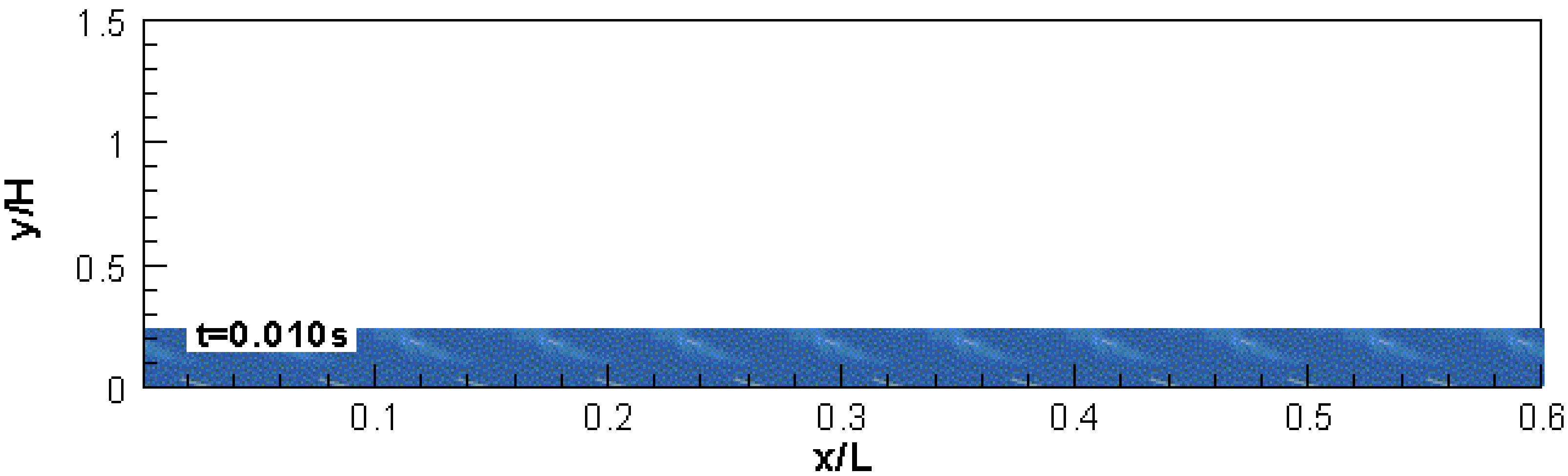
Level-set calculations by J.Hernandez *et al* at the International PHOENICS Conference in Moscow 2002



3. EXTENSION TO MULTI-PHASE FLOW
3.1 Overview (end)

Examples of **dispersed-flow** phenomena include:

- vaporisation of **water droplets** injected into an air stream in order to cool and humidify it;
- **pool boiling** in a kettle;
- **dissolution of granulated sugar** in a stirred cup of tea;
- flow of **liquid and vapour** in the shell of a nuclear-plant steam-generator;
- cooling of a **fluidised-bed reactor** by a cold-water-containing tube bundle immersed within it;
- vaporisation, ignition and combustion of **oil droplets** sprayed into a **Diesel engine**; and
- burning of, and radiation from, **pulverised coal in a power-station furnace.**

3.2 Research opportunities in respect of dispersed flows

The two-phase idealisation.

Computer simulation of **dispersed-flow** phenomena is always based on the **neglect** of some of the features of the real situation. For example:

- although in fact **bubbles** of many **different sizes** exist at a particular location in a boiler, they are usually supposed all to have the **same** size there;

- although some **coal particles** have greater **velocities** than others at a particular place in a furnace, the **differences are disregarded.**

- These presumptions make it possible to regard the true **multi-**phase mixture as being a **two-**phase one.

3.2 Research opportunities in respect of dispersed flows (contd)

Dispersed two-phase flows are **familiar to us** all; yet traditional CFD ignores them.

An example of two-phase flow computation.

Consider the steady flow of a two-phase mixture in a '**turn-around duct**'.

The two fluids may be thought of as **air** and **water**, with a density ratio of **1:1000.**

Centrifugal force flings the **water** to the **outside** of the bend pushing the **air** to the **inside.**

This is what I call the **sifting** phenomenon, wherein **intermingled fluids move relative to one another** under the influence of **body forces**.

3.2 Research opportunities in respect of dispersed flows
(contd)

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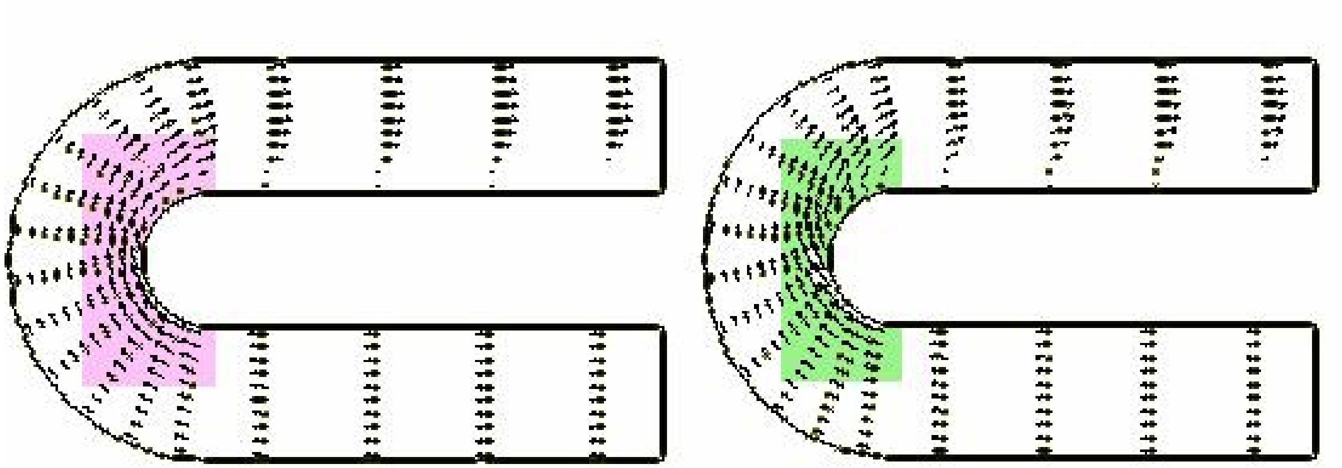
Here are the **computed velocity vectors**.



Air velocity vectors

Water velocity vectors

Their angles differ near the inner wall of the bend.

3.2 Research opportunities in respect of dispersed flows
(contd)

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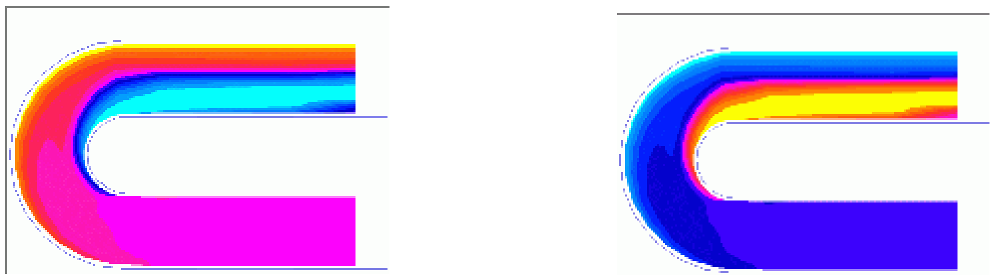
Their **volume-fraction contours**, shown here, confirm the relative movements of the two

Phases: they have been '**cyclonically separated**'.

Water **Air**



Yellow = high; light blue = low

The computations should be studied even by those interested only in **single-phase** flow; for **a similar 'sifting' motion** would be observed if the two fluids had **equal densities** but differing **velocities**. This is how the **turbulent flows in curved ducts** are to be understood.

I shall return to this in connection with **population analysis.**

3.2 Research opportunities in respect of dispersed flows (contd)

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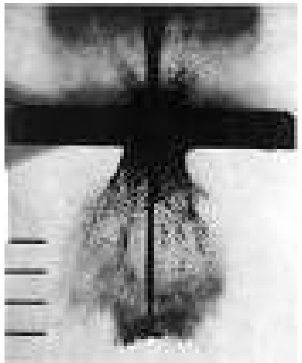
Here is another **scarcely-explored field** of two-phase study: the **collapse of buildings**

The **penetration of armour** by explosive devices has long been simulated by recognising that **metals** under very **high pressure** can **flow like fluids**

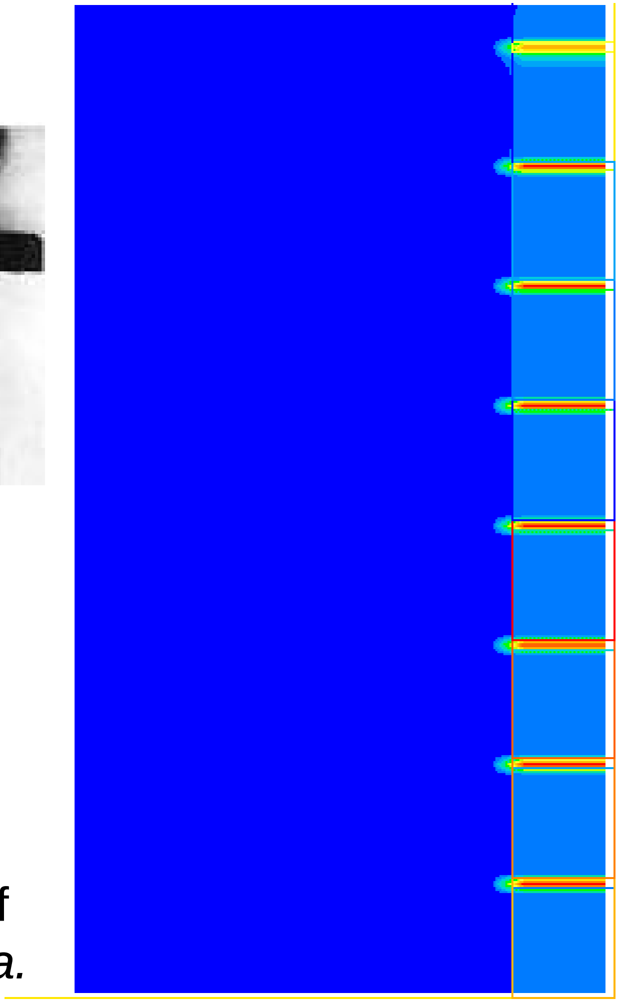


So can other solids: **fragmented concrete** for example.

Why did the World Trade Center **Twin Towers** collapse so quickly on **September 11**?

The pressure generated as the **higher floors** fell on the next below **'fluidised'** that one too; and so on to **Ground Zero**.

On the right is a **two-phase-flow simulation** of the process. Blue is air, red is concrete *etcetera.*



4. EXTENSION TO THE POPULATION DIMENSION

4.1 Introduction by reference to turbulent combustion

Highlights of my personal exploration of the **population dimension** have been**:**

1. **Scurlock's** unaccountable turbulent-flame findings (1948)
2. The **Eddy-Break-Up model** (1971)**,** which explained **some** of them
3. The **Four-Fluid** model (1995), which explained **more**
4. The **Multi-Fluid** model with **a one-dimensional** population
5. The **Multi-Fluid** model with **a two-dimensional** population

Here I merely summarise.

4.1 Introduction by reference to turbulent combustion (contd)

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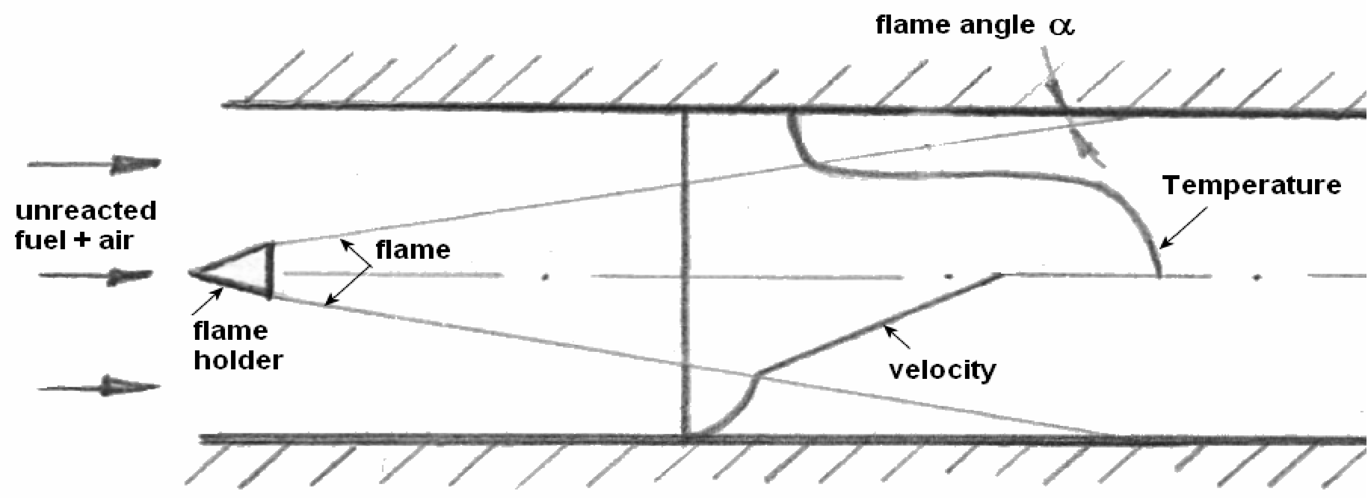
Scurlock (1948) discovered that the speed of turbulent flame propagation in a plane-walled duct was approximately:

- **proportional to the velocity** of the incoming gas stream,
- **independent of the turbulence** intensity of this stream, and
- **independent of its fuel-air ratio** and indeed of
- the **choice of fuel**, all of which however **did** affect the incoming velocity which caused **sudden extinction.** **Why? Why? Why?**



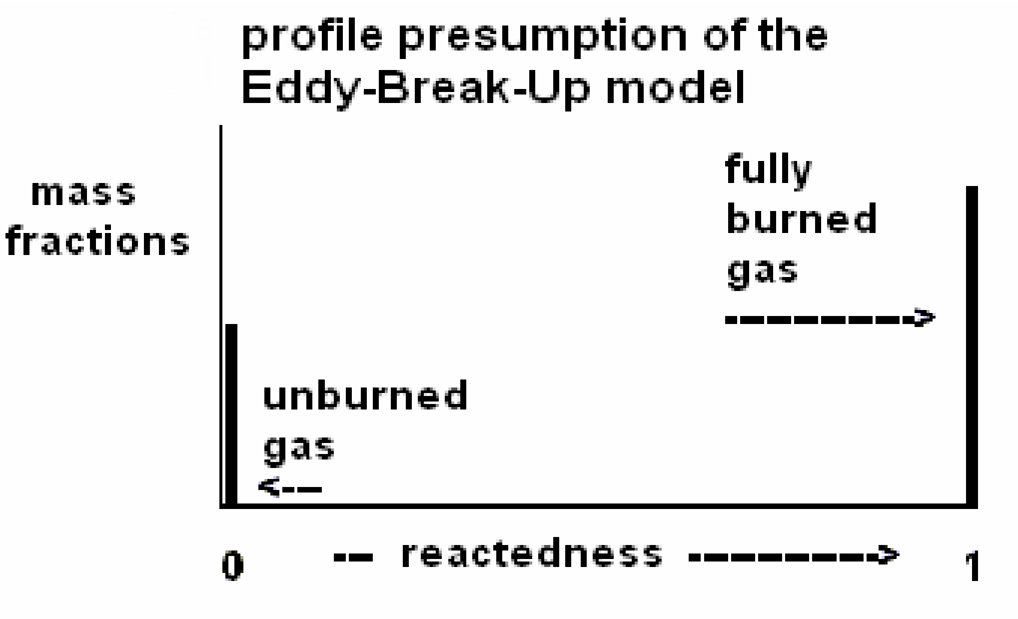
4.1 Introduction by reference to turbulent combustion (contd)

The **Eddy-Break-Up model** of 1971 explained the flame-speed finding by **presuming** the burning gases to comprise a **two-component population**, consisting of:

1. wholly **un-reacted gas** fragments, too cold to burn, and
2. **hot fully-reacted** gas fragments, which also could not burn.

These **collided** at a rate proportional to their volume-fraction product and to the **turbulence intensity**, producing intermediate gas which **could burn instantly.**

The EBU became popular and is still **(too!)** widely used.



4.1 Introduction by reference to turbulent combustion (contd)

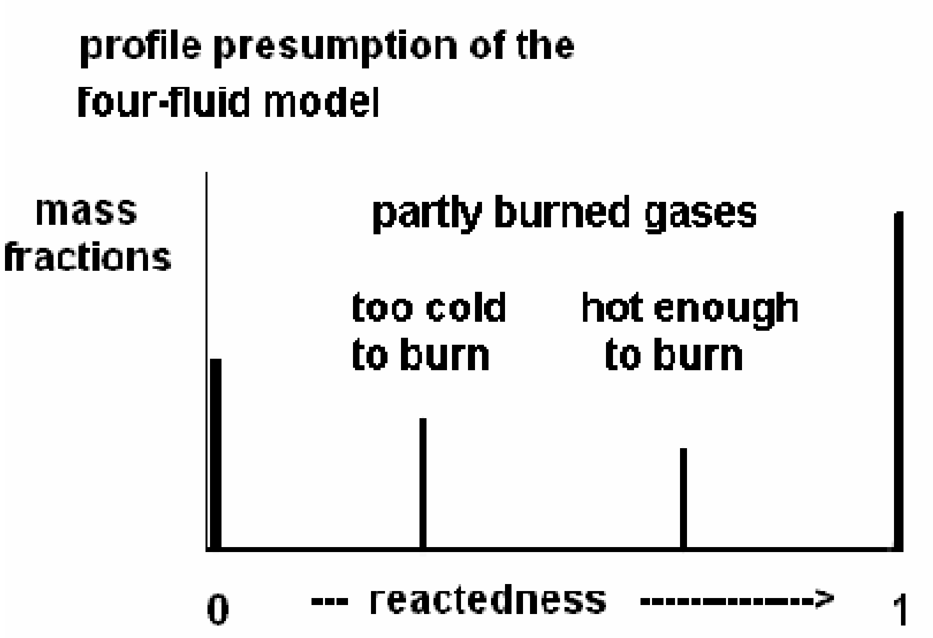
The **four-fluid** model (1995) **refined the population grid,** as shown here**.**

All **four** fluids could collide; but only one could react, at a **chemical-kinetically limited** rate.

Unlike EBU, this model **could** explain Scurlock's sudden-extinction findings.

The next step was obvious,

viz. the **(one-dimensional) multi-fluid model.**



The four-fluid extension to EBU

4.1 Introduction by reference to turbulent combustion (contd)

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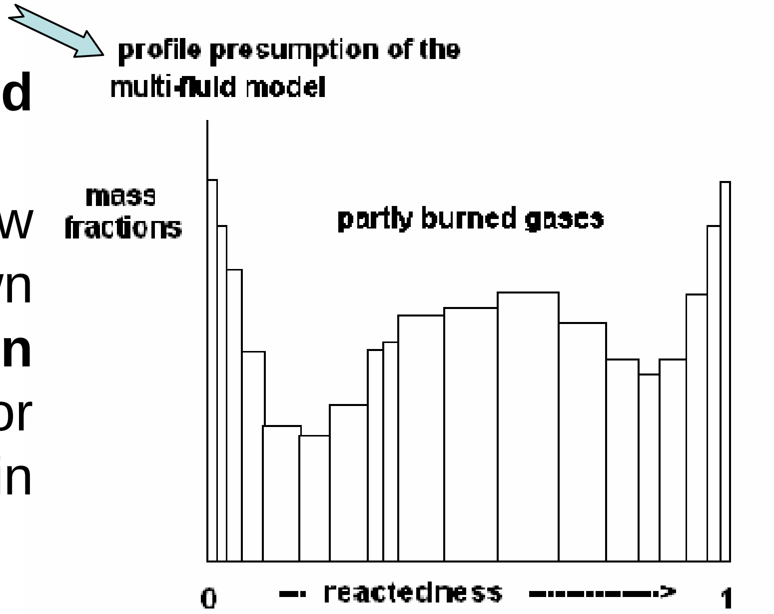
The multi-fluid extension of EBU

Why not **refine the population grid** further, as shown here?
Each **histogram ordinate** is now the dependent variable of its own standard **conservation equation** **plus** **source/sink terms** for **reaction** (*i.e.* 'convection in reactedness space') and **collision**.



The equations, solved by any sufficiently-flexible CFD code, result in **computed** (*i.e.* **not** presumed) **population profiles**.
Just so did finite-volumes replace presumed profiles in CFD.
Here **FVM** has been **extended** to the **population dimension**.

4.1 Introduction by reference to turbulent combustion (contd)

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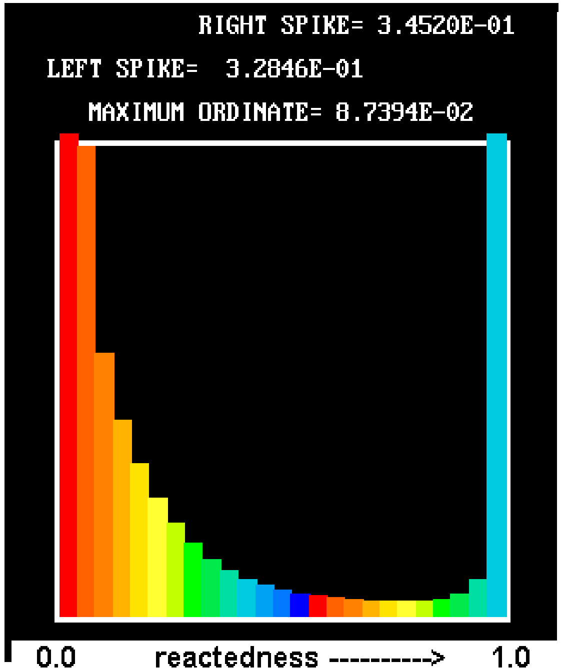
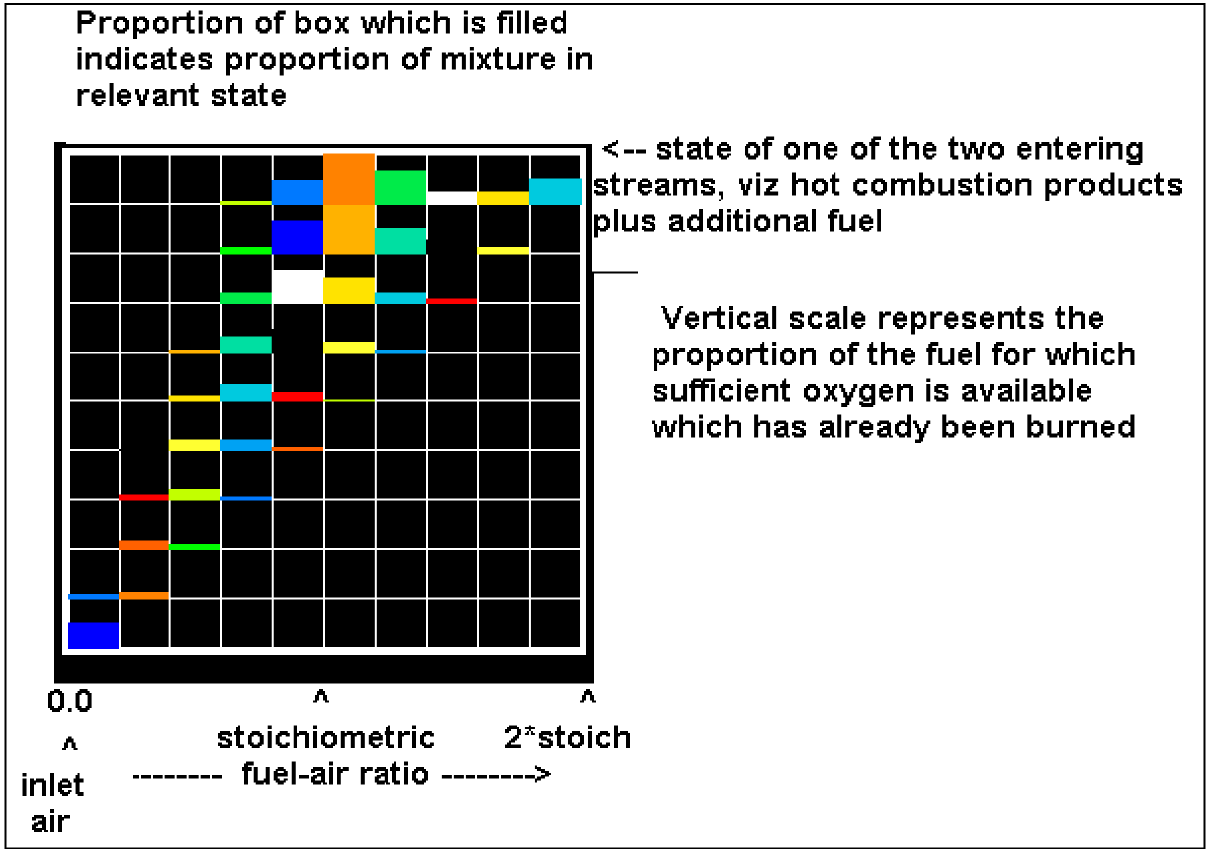
- Calculations have shown why EBU has worked so well: with fast chemical kinetics the **distribution does show high spikes** at zero and unity reactedness.
- Calculations also allow determination of **how many fluids** are needed for accuracy.
- The **analogy** with **spatial-**grid-refinement tests is very close.
- Of course, the **computer time increases**, as expected, with the number of 'fluids' (*i.e.* population components, histogram ordinates)
- Interestingly, no case of divergence has ever arisen



Examples shown so far (for EBU, 4-fluid and MFM) have all had **one** population dimension, reactedness.
The **fuel/air ratio** can also be used for MFM as the second **dimension**.

4.1 Introduction by reference to turbulent combustion (contd)

Computations for a 2D population of burning fuel and air are shown below. Each square represents a population **component.** The extent to which it is filled represents its **prevalence** in the population.



4.3 Research opportunities
(contd)

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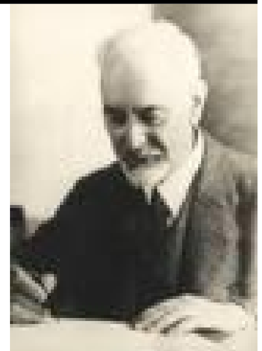
Desirable conceptual advances:



- The **Prandtl's mixing-length** concept is an **inspired guess** about how colliding fragments of fluid **might** interact.
- It concerns interactions between **neighbouring locations** in **geometrical** space.

- In **population space,** there are **some** interactions between **neighbouring locations**: thus reacting material passes from a **lower**- to a **higher**-reactedness component.
- But there are **also** interactions between **remote components**, namely collisions between gases of **very different** reactedness.

If **Ludwig Prandtl** had asked himself:
How **collisions** affect **population,** would he have thought about Gregor Mendel?

4.3 Research opportunities
(contd)

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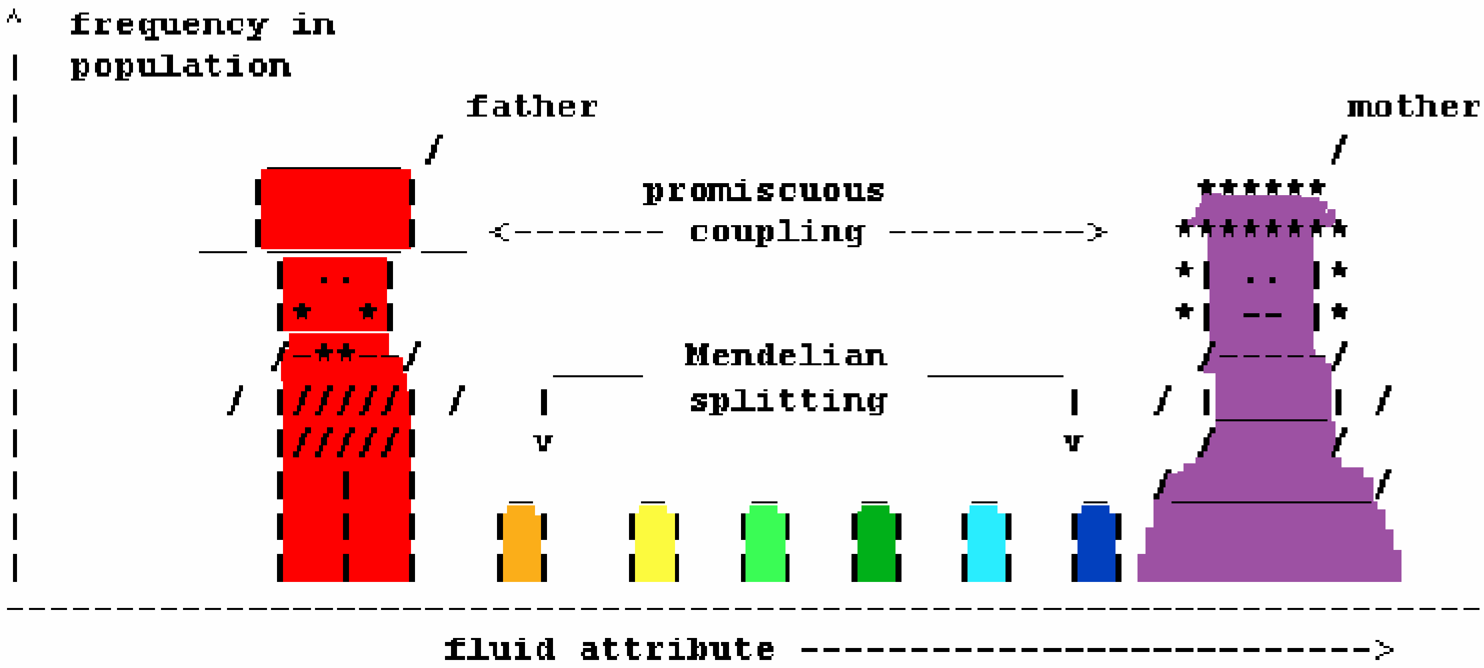
The first MFM employs the **'Promiscuous-Mendelian'** hypothesis: this implies that **any** pair can procreate; and their offspring share their parents' attributes, **uniformly graded**.



Who can provide a **better** one? See printed paper for some ideas.

4.3 Research opportunities
(contd)

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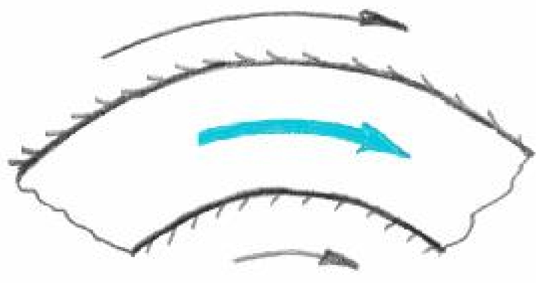
Experimental opportunities; scientific and industrial
Would someone please **measure the population distributions**, so that the hypotheses can be checked and then improved?
And how about testing experimentally what has been predicted about **gas-turbine combustors** and **stirred reactors?**

Computational opportunities
I have used **fixed, uniform** and **structured population grids.**. Who will extend to **them** our knowledge of **moving, non-uniform, unstructured, problem-adaptive** and other sophisticated **geometric grids?**

Pure-hydrodynamics opportunities
A '**round-the-bend' idea:** I believe that allowing high-velocity population members to **'sift'** through lower-velocity ones will explain **swirling-flow observations**. Is it not at least worth a try?

4.3 Research opportunities
The ‘round-the-bend’ idea explored. 1

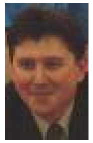
How try?



- Take a **general-purpose CFD code** having **population-dimension** capability.
- Envisage a **turbulent swirling** flow, between cylinders rotating at different speeds.
- Select a **multi-fluid turbulence model,** with **circumferential velocity** as the **population-defining** attribute.
- Choose a high Reynolds Number for which **turbulent-diffusion** and **inter-fluid-collision** processes are of the same order of magnitude**.**
- **Postulate** that radial **‘sifting velocity’** depends on the radial **body forces** being **different for each fluid.** This needs **new thinking.**
- **Vary** this force **systematically,** by changing curvature; then observe the effects on **velocity-population distribution**, shear stress, *etc.*

I have done this, as **anyone** could have done. **A few results** now follow.

4.3 Research opportunities
The ‘round-the-bend’ idea explored. 2

1. The general-purpose CFD code which I used was **PHOENICS**.
2. A **steady, rotating, turbulent** flow between two cylinders was set up in a ‘**switch-on’** manner**.**
3. The **17-fluid model** of Zhubrin  and Pavistkiy  was selected.
4. **Turbulent-diffusion/collision-rate ratios** were chosen, based on **experimental data** for channel flow.
5. **A body force proportional to fluid velocity** was postulated (velocity-**squared** might have been more realistic).
6. A **new** slip-velocity-proportional-to-body-force-difference **hypothesis** was formulated. This hypothesis was **conveyed to PHOENICS** by way of the **In-Form** feature; **no new programming** or executable-building was needed.

The computations, of which the results will be displayed, employed only **standard features** of PHOENICS**.**

4.3 Research opportunities
The 'round-the-bend' idea explored, 3

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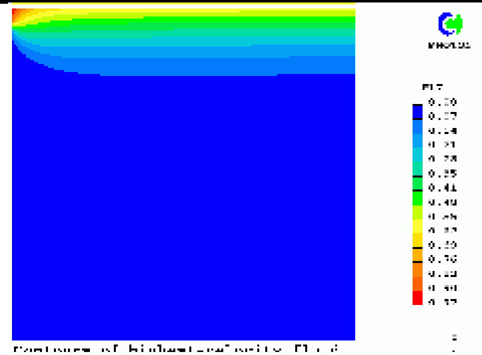
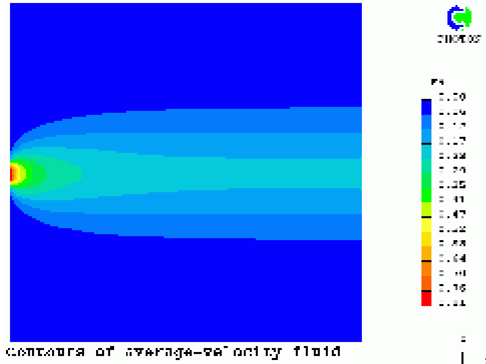
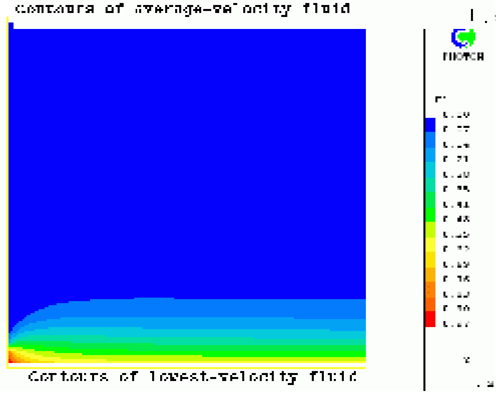
Here are results for **zero curvature**, *i.e.* **no** swirl.They are **contours** of **computed mass fractions** of individual population components.
Flow is **from left to right**.
First, the **highest-velocity** fluid, which is clearly concentrated near the upper, higher-velocity wall.



Next, contours for the **9th fluid** with velocity equal to the mean wall velocity. They spread as a consequence of turbulent **diffusion opposed by collision.** Downstream cessation of spread implies that the two processes are **in balance**.



Here are contours of the **lowest-velocity** fluid.
Its concentrations are high near the **low-velocity** wall, *ts spread also* **ceases downstream.**



Diagrams for **all 17 fluids** have been computed; but to display them all would be tedious.

4.3 Research opportunities
The ‘round-the-bend idea explored, 4

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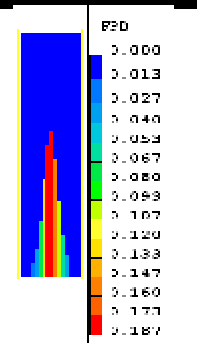
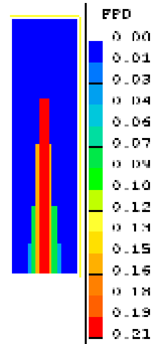
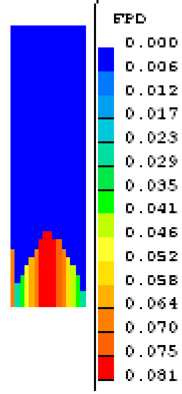
The **fluid-population distributions** (**FPD**s) have also been computed. Here is that for the **central plane**, when the duct is **not curved**. **Fluid-9** has the highest mass fraction, *viz* 0.187**.** **Results** for **curved ducts** will now be shown**.**



Here is the corresponding FPD for **radius increasing with** average velocity; the distribution becomes **narrower .**
The **fluid-9 mass fraction has risen** to 0.21.
Faster fluids **sift** towards **the faster-moving outer wall.**



Now the **direction of curvature is changed**. Faster-moving fluids now **sift away from** the faster-moving, **now inner** wall. The shape of the FPD **broadens** dramatically. **Fluid-9 mass fraction has fallen** to 0.81, and the **shear stress increases**.



These results explain why flows near **convex** and concave walls are so **different**. Only **population models** can begin to simulate **swirling- flow behaviour.**
They should be **vigorously developed** and **used.**.

4.3 Research opportunities
The round-the-bend idea, 5. Conclusion

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Heat & mass transfer & hydrodynamics in swirling flow

What I have shown is the result of a **few days work** by an 85-year-old. Perhaps **interesting**; but **hardly conclusive**.

Why can I not report on, and praise, what the younger generation is doing to **explore the fluid-population dimension of CFD**? Because **such work does not exist**.

Why does it not exist? Because the younger generation **does little but copy** Kolmogorov and Harlow and Spalding and Launder and Rodi and other old men, whose ideas they seem reluctant **to challenge!** They should be **less in awe of them.**

Perhaps also they suppose it would be **difficult to get started**. That is **incorrect** as I hope to have shown. Let it now be understood that **the door is wide open.**

5. CONCLUDING REMARKS

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My **message** is that It is our **duty** to **enlarge the frontiers of Computational Heat Transfer and Fluid Dynamics.**

Neighbouring territories which especially deserve our liberating attentions include:

1. **Solid-stress**-land, which needs a complete **change of regime**,
2. **Multi-phase-flow**-land, which is **insufficiently cultivated**,
3. **Chemical-reaction**-land where the ruling **intelligentsia care too little** about the workers' needs.

But let us make sure that the forces which occupy territories 2 and 3 are well-trained in distinguishing the **significant attributes of the populations**.

They will then be ready to invade and rule over **swirling-flow-land** too.

5. CONCLUDING REMARKS
(concluded)

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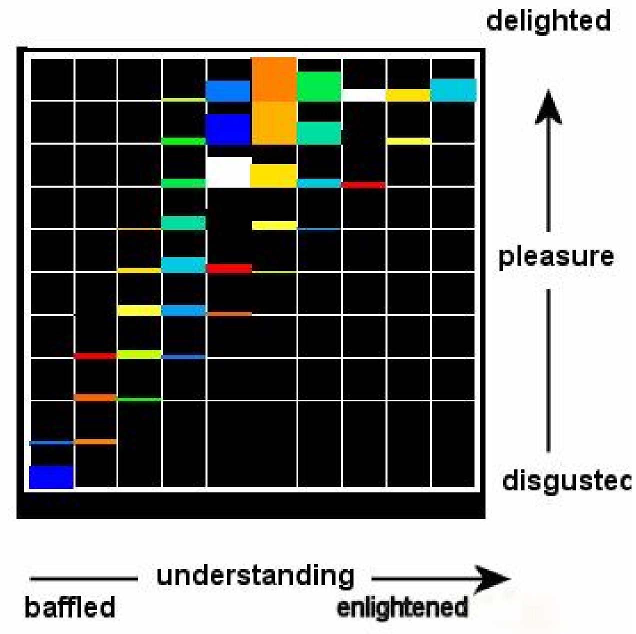
In this lecture room, a **two-dimensional population** exists, with the significant attributes:

1. **Understanding** (0=baffled; 1=enlightened);
2. **Pleasure** (0=disgusted; 1= delighted)

What, I ask myself, would **its histogram** look like?

I shall be not displeased if it is something like the one I showed earlier for a reactor.

This would show that the majority understood about half; but more than half enjoyed it.



But whichever box each of you is placed in, I thank you for your attention.