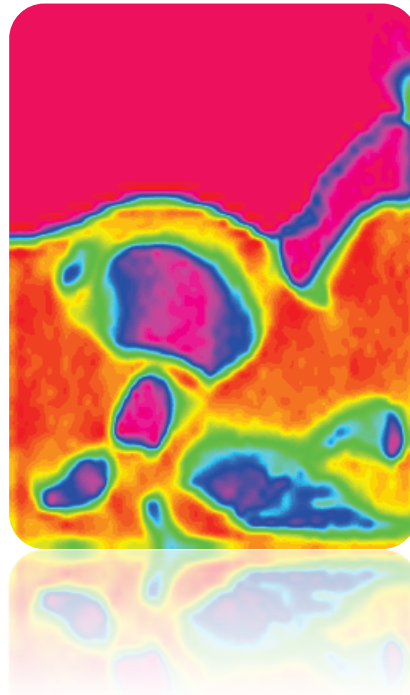


# COMPUTATIONAL FLUID DYNAMICS - A STEPPING-STONE OF MULTIPHYSICS



# PRESENTATION OVERVIEW

## ❑ INTRODUCTION

- Presenter's Bio

## ❑ HISTORICAL PERSPECTIVE

- Evolution of Fluid Mechanics
- Computational Fluid Dynamics (CFD)
- Semi-Implicit Pressure Linked Equation (SIMPLE)
- Words of Caution
- Colorful Fluid Dynamics
- CFD Today

## ❑ PROJECT EXAMPLES

- Micro-Fluidic Valve (NUST, CALTECH)
- Fluidized Bed (CAMBRIDGE, ETH ZURICH)
- Shock-Tube (NFR, LILLE)
- Fluid Viscosity-Density Sensor (INNOSUISSE, RHEONICS GmbH)
- Environment Exposure Sensor (WINDTECH AS)

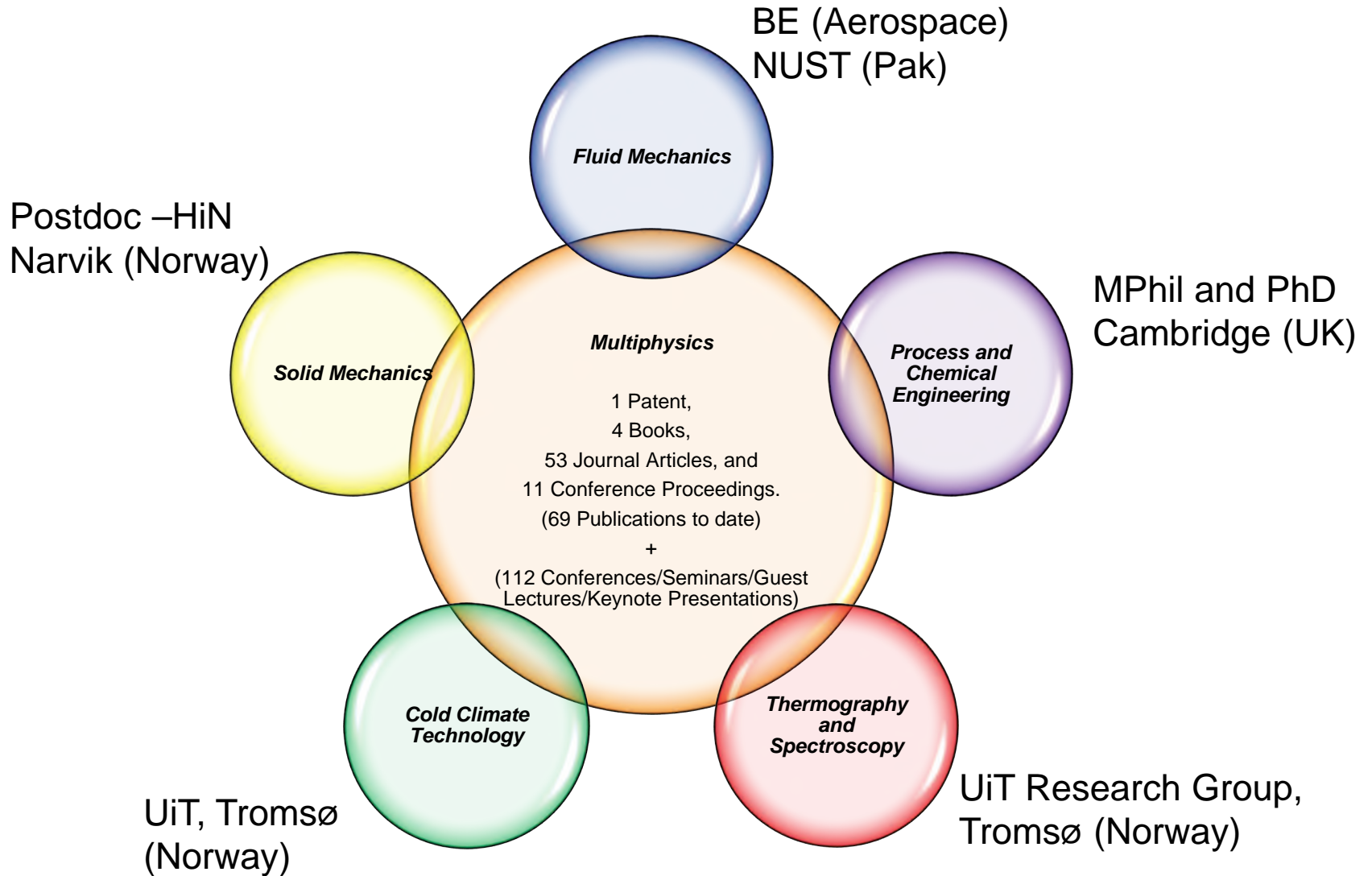
# PRESENTER'S BIO



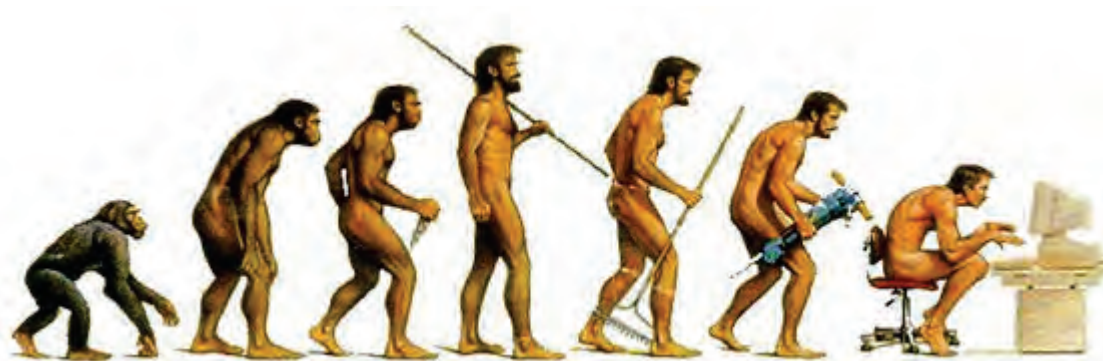
# PRESENTER'S BIO



# PRESENTER'S BIO



# EVOLUTION OF FLUID MECHANICS (HISTORICAL PRESPECTIVE)



**Newton  
(1686)**

**Bernoulli  
(1738)**

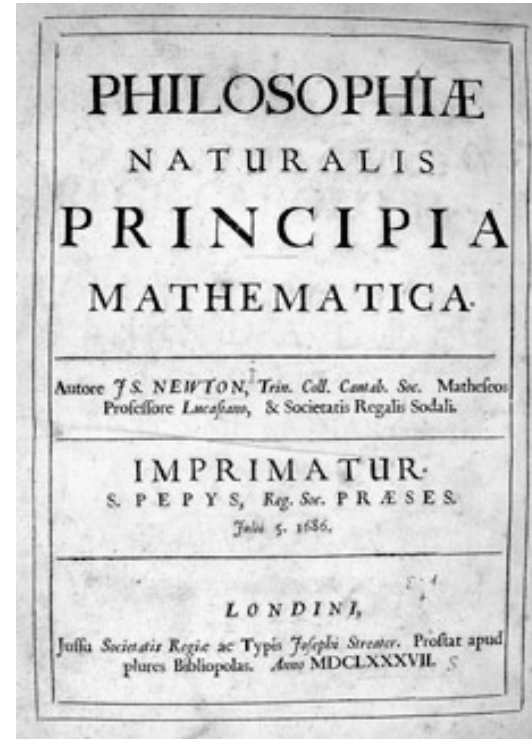
**Euler  
(1757)**

**Navier  
(1822)**

**Stokes  
(1845)**

**CFD\*  
(1922)**

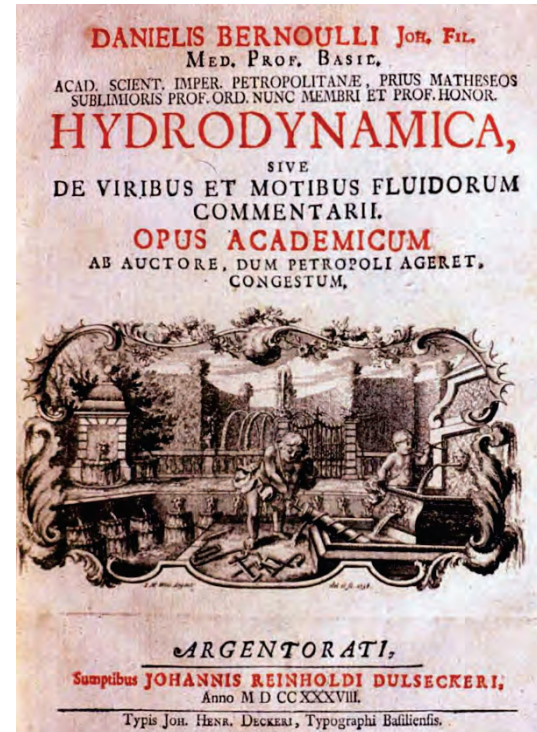
# NEWTON (1686)



$$F = ma$$



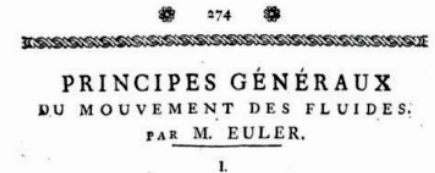
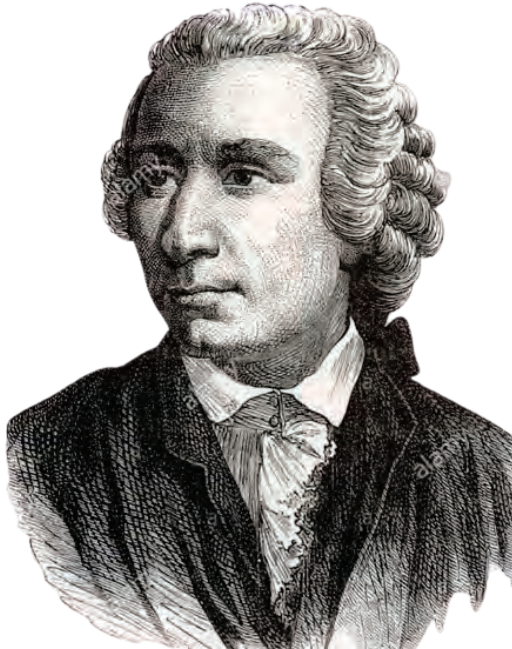
# BERNOULLI (1738)



$$p_0 + \frac{1}{2} \rho v_0^2 + \rho g h_0 = \text{constant}$$



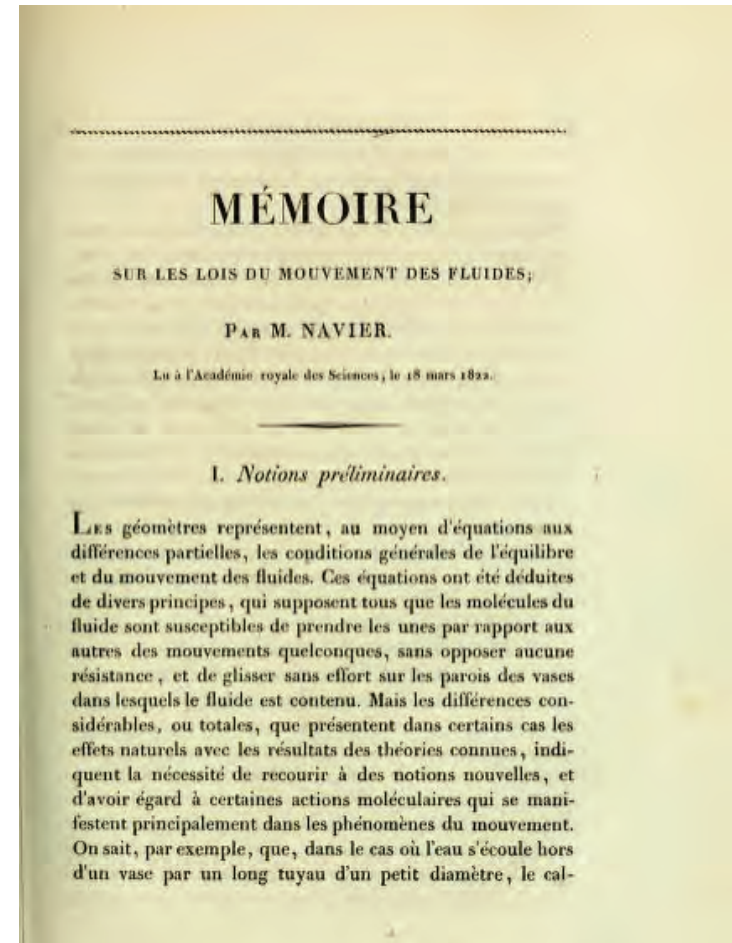
# EULER (1757)



Avant établi dans mon Mémoire précédent les principes de l'équilibre des fluides le plus généralement, tant à l'égard de la diverse qualité des fluides, que des forces qui y puissent agir; je me propose de traiter sur le même pied le mouvement des fluides, & de rechercher les principes généraux, sur lesquels toute la science du mouvement des fluides est fondée. On comprend aisément que cette matière est beaucoup plus difficile, & qu'elle renferme des recherches incomparablement plus profondes: cependant j'espère d'en venir aussi heureusement à bout, de sorte que s'il y reste des difficultés, ce ne sera pas du côté du mécanique, mais uniquement du côté de l'analytique: cette science n'étant pas encore portée à ce degré de perfection, qui seroit nécessaire pour développer les formules analytiques, qui renferment les principes du mouvement des fluides.

II. Il s'agit donc de découvrir les principes, par lesquels on puisse déterminer le mouvement d'un fluide, en quelque état qu'il se trouve, & par quelques forces qu'il soit sollicité. Pour cet effet examinons en détail tous les articles, qui constituent le sujet de nos recherches, & qui renferment les quantités tant connues qu'inconnues. Et d'abord la nature du fluide est supposée connue, dont il faut considérer les diverses espèces: le fluide est donc, ou incompressible, ou compressible. S'il n'est pas susceptible de compression, il faut distinguer deux cas, l'un où toute la masse est composée de parties homogènes, dont la densité est partout & demeure toujours la même, l'autre

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$
$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\mathbf{u} \otimes (\rho \mathbf{u})) + \nabla p = 0$$
$$\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{u} (E + p)) = 0$$



$$(\lambda + \mu)\nabla(\nabla \cdot \mathbf{u}) - \mu\nabla \times (\nabla \times \mathbf{u}) = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}$$

# STOKES (1845)



ON THE EFFECT OF THE INTERNAL FRICTION OF FLUIDS ON THE MOTION OF PENDULUMS

## ON THE EFFECT OF THE INTERNAL FRICTION OF FLUIDS ON THE MOTION OF PENDULUMS

Sir George Gabriel Stokes

[Read December 9, 1850.]

[From the *Transactions of the Cambridge Philosophical Society*, Vol. IX, p. 16]  
Reprinted in *Mathematical and Physical Papers, Sir George Gabriel Stokes and Sir J. Larmor*, Vol. 1, 1889-1897

THE great importance of the results obtained by means of the pendulum has induced philosophers to devote so much attention to the subject, and to perform the experiments with such a scrupulous regard to accuracy in every particular, that pendulum observations may justly be ranked among those most distinguished by modern exactness. It is unnecessary here to enumerate the different methods which have been employed, and the several corrections which must be made, in order to deduce from the actual observations the results which would correspond to the ideal case of a simple pendulum performing indefinitely small oscillations in vacuum. There is only one of these corrections which bears on the subject of the present paper, namely, the correction usually termed the *reduction to a vacuum*. On account of the inconvenience and expense attending experiments in a vacuum apparatus, the observations are usually made in air, and it then becomes necessary to apply a small correction, in order to reduce the observed result to what would have been observed had the pendulum been swung in a vacuum. The most obvious effect of the air consists in a diminution of the moving force; and consequent increase in the time of vibration, arising from the buoyancy of the fluid. The correction for buoyancy is easily calculated from the first principles of hydrostatics, and formed for a considerable time the only correction which it was thought necessary to make for reduction to a vacuum. But in the year 1828 Bessel, in a very important memoir in which he determined by a new method the length of the seconds' pendulum, pointed out from theoretical considerations the necessity of taking account of the inertia of the air as well as of its buoyancy. The numerical calculation of the effect of the inertia forms a problem of hydrodynamics which Bessel did not attack; but he concluded from general principles that a fluid, or at any rate a fluid of small density, has no other effect on the time of very small vibrations of a pendulum than that it diminishes its gravity and increases its moment of inertia. In the case of a body of which the dimensions are small compared with the length of the suspending wire, Bessel represented the increase of inertia by that of a mass equal to  $k$  times the mass of the fluid displaced, which must be supposed to be added to the inertia of the body itself. This factor  $k$  he determined experimentally for a sphere a little more than two inches in diameter, swung in air and in water. The result for air, obtained in a rather indirect way, was  $k = 0.9459$ , which value Bessel in a subsequent paper increased to 0.956. A brass sphere of the above size having been swung in water with two different lengths of wire in succession gave two values of  $k$ , differing a little from each other, and equal to only about two-thirds of the value obtained for air.

The attention of the scientific world having been called to the subject by the publication of Bessel's memoir, fresh researches both theoretical and experimental soon appeared. In order to examine the effect of the air by a more direct method than that employed by Bessel, a large vacuum apparatus was erected at the expense of the Board of Longitude, and by means of this apparatus Captain (now Colonel) Sabine determined the effect of the air on the time of vibration of a particular invariable pendulum. The results of the experiments are contained in a memoir read before the Royal Society in March 1829, and printed in the *Philosophical Transactions* for that year. The mean of eight very consistent experiments gave 1.655 as the factor by which for that pendulum the old correction for buoyancy must be multiplied in order to give the whole correction on account of the air. A very remarkable fact was discovered in the course of these experiments. While the effects of air at the atmospheric pressure and under a pressure of about half an atmosphere were found to be as nearly as possible proportional to the densities, it was found that the effect of hydrogen at the atmospheric pressure was much greater, compared with the effect of air, than corresponded with its density. In fact, it appeared that the ratio of the effects of hydrogen and air on the times of vibration was about 1 to 5 1/4, while the ratio of the densities is only about 1 to 13. In speaking of this result Colonel Sabine remarks, "The difference of this ratio from that shown by experiment is greater than can well be ascribed to accidental error in the experiment, particularly as repetition produced results almost identical. May it not indicate an inherent property in the elastic fluids, analogous to that of viscosity in liquids, of resistance to the motion of bodies passing through them, independently of their density? a property, in such case,

$$\rho \frac{Du}{Dt} = -\nabla p + \nabla \cdot \tau + \rho g$$



CLAY  
MATHEMATICS  
INSTITUTE



## NOTABLE OTHERS (CFD)



Joseph-Louis Lagrange  
(1736-1813)



Siméon Denis Poisson  
(1781-1840)



Augustin-Louis Cauchy  
(1789-1857)



Jean Léonard Marie Poiseuille  
(1791-1869)



Ludwig Eduard Boltzmann  
(1844-1906)

## NOTABLE OTHERS (FLUID MECHANICS)

- Archimedes 287-212 B.C.
- Sextus Julius Frontinus 40-103 B.C.
- Leonardo daVinci 1452-1519
- Galileo Galilei 1564-1642
- Evangelista Torricelli 1608-1647
- Edme Mariotte 1620-1684
- Blaise Pascal 1623-1662
- **Sir Isaac Newton 1642-1727**
- Henri de Pitot 1695-1771
- **Daniel Bernoulli 1700-1782**
- **Leonard Euler 1707-1783**
- Jean de Rond d'Alembert 1717-1783
- Antoine Chezy 1718-1798
- Jean Charles Borda 1733-1799
- **Joseph-Louis Lagrange 1736-1813**
- Giovanni Battista Venturi 1746-1822
- Pierre-Simon Laplace 1749-1827
- **Siméon Denis Poisson (1781-1840)**
- **Claude Louis Marie Navier 1785-1836**
- **Augustin Louis de Cauchy 1789-1857**
- **Jean Louis Poiseuille 1791-1869**
- Gotthilf H. Ludwig Hagen 1797-1884
- Henri Philibert Darcy 1803-1858
- Julius Weisbach 1806-1871
- William Froude 1810-1879
- Robert Manning 1816-1897
- **George Gabriel Stokes 1819-1903**
- Ernst Mach 1838-1916
- Osborne Reynolds 1842-1912
- Lord Rayleigh [John William Strutt] 1842-1919
- **Ludwig Eduard Boltzmann 1844-1906**
- Vincez Strouhal 1850-1922
- Edgar Buckingham 1867-1940
- Moritz Weber 1871-1951
- Ludwig Prandtl 1875-1953
- Lewis Ferry Moody 1880-1953
- Theodor von Karman 1881-1963
- Paul Richard Heinrich Blasius 1883-1970
- And others...

*"If I have seen farther than others, it is because I was standing on the shoulders of giants."*

**Sir Isaac Newton**

# COMPUTATIONAL FLUID DYNAMICS (1922)



An arrangement of meteorological stations designed to fit with the chief mechanical properties of the atmosphere. Other considerations have been disregarded. Pressure to be observed at the centre of each shaded oblong, velocity at the centre of each white oblong. The numerical coordinates refer to these centres as also do the names, although as to the latter there may be errors of 5 or 10 km. The word "with" in "with Jeanmarte will, Dieppe" etc. is intended to suggest an interpolation between observations made at the two places. See page 9, and Chapters 3 and 7. (Contrast the existing arrangement shown on p. 184.)

## WEATHER PREDICTION BY NUMERICAL PROCESS

BY  
LEWIS F. RICHARDSON, B.A., F.R.MET.SOC., F.INST.P.  
FORMERLY SUPERINTENDENT OF ESKDALEMOUTH OBSERVATORY  
LECTURER IN PHYSICS AT WETMINSTER TRAINING COLLEGE

$\Delta t = 12, 24h$   
 $\Delta p = 150mb !$   
*numerically unstable !*

L.F. Richardson (1922)  
Weather Prediction by Numerical Process,  
Cambridge University Press

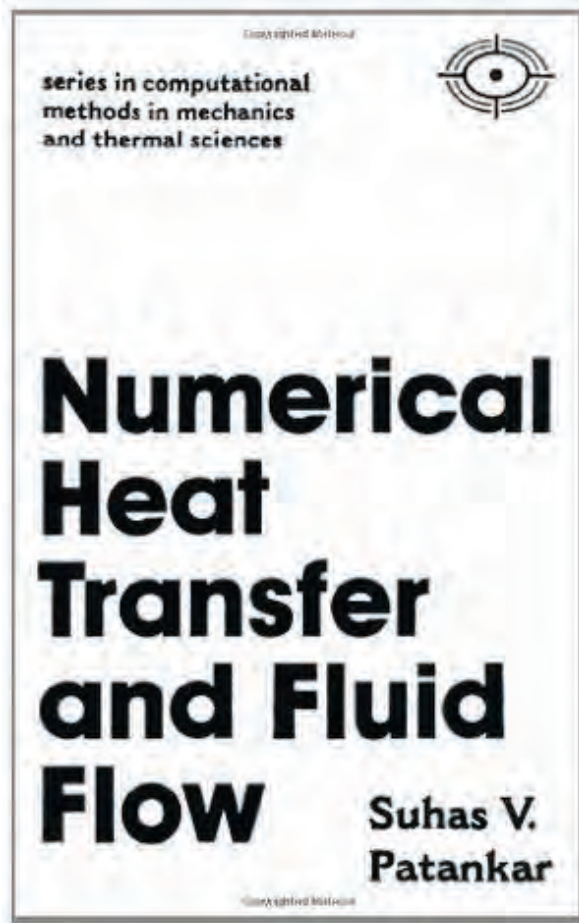
CAMBRIDGE  
AT THE UNIVERSITY PRESS  
1922



Lewis Fry Richardson  
(1881 – 1953)



# SEMI-IMPLICIT PRESSURE LINKED EQUATION (1979)



Shuhas V. Patankar  
(1941-)



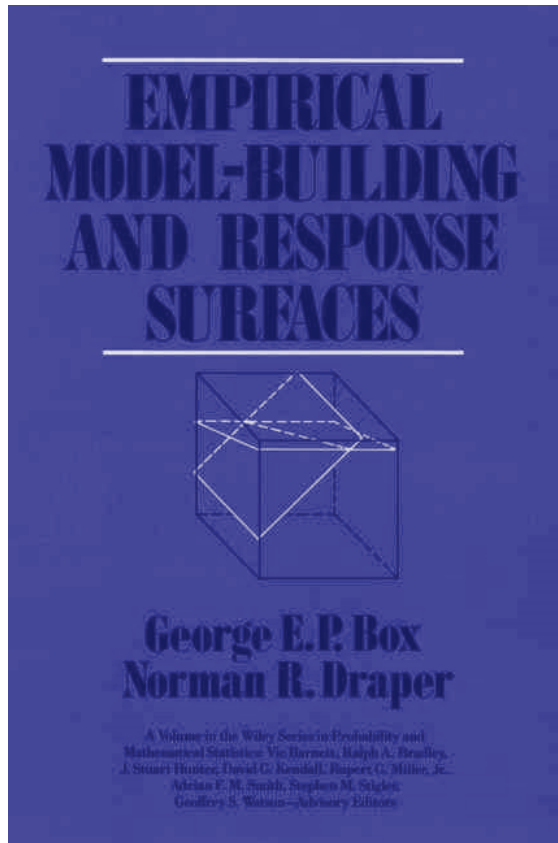
Dudley Brian Spalding  
(1923 – 2016)



## WORDS OF CAUTION - MODELS (1987)

*“Essentially, all models are wrong, but some are useful,”*

*“Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful.”*

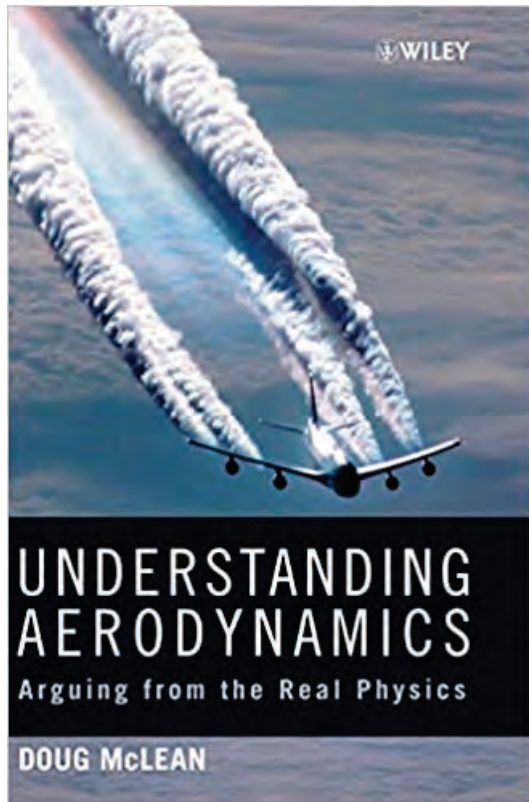


George E. P. Box  
(1919 – 2013)



# COLORFUL FLUID DYNAMICS

*“These days it is common to see a complicated flow field, predicted with all the right general features and displayed in glorious detail that looks like the real thing. Results viewed in this way take on an air of authority out of proportion to their accuracy. In this regard, modern CFD is a very seductive thing”*



Doug McLean  
(1919 – 2013)

# COLORFUL FLUID DYNAMICS

*“Even inaccurate CFD can be useful”*

*“The power of detailed visualization makes CFD richer in information than experiment”*

JOURNAL OF COMPUTATIONAL PHYSICS 43, 357–372 (1981)

## Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes

P. L. ROE

Royal Aircraft Establishment, Bedford, United Kingdom

Received August 14, 1980; revised March 30, 1981

Several numerical schemes for the solution of hyperbolic conservation laws are based on exploiting the information obtained by considering a sequence of Riemann problems. It is argued that in existing schemes much of this information is degraded, and that only certain features of the exact solution are worth striving for. It is shown that these features can be obtained by constructing a matrix with a certain “Property U.” Matrices having this property are exhibited for the equations of steady and unsteady gasdynamics. In order to construct them, it is found helpful to introduce “parameter vectors” which notably simplify the structure of the conservation laws.

### INTRODUCTION

We consider the initial-value problem for a hyperbolic system of conservation laws, i.e., we seek a vector  $\mathbf{u}(x, t)$  such that

$$\mathbf{u}_t + \mathbf{F}_x = 0, \quad (1)$$

and

$$\mathbf{u}(x, 0) = \mathbf{u}_0(x), \quad (2)$$

where  $\mathbf{F}$  is some vector-valued function of  $\mathbf{u}$ , such that the Jacobian matrix  $A = \partial\mathbf{F}/\partial\mathbf{u}$  has only real eigenvalues.

We introduce the discrete representation  $x_i = x_0 + i \Delta x$ ,  $t_n = t_0 + n \Delta t$ , and suppose that  $\mathbf{u}_i^n$  is some approximation to  $\mathbf{u}(x_i, t_n)$ .

A multitude of strategies have been devised to obtain numerical results for the discrete problem, and their relative merits are still largely unclear. We shall address in this paper some questions relating to those methods which attempt to construct the solution by solving a succession of Riemann problems. Recall that the Riemann problem is the initial-value problem obtained when the general data, Eq. (2), is specialised to

$$\mathbf{u}(x, 0) \equiv \mathbf{u}_L \quad (x < 0); \quad \mathbf{u}(x, 0) \equiv \mathbf{u}_R \quad (x > 0). \quad (3)$$

357

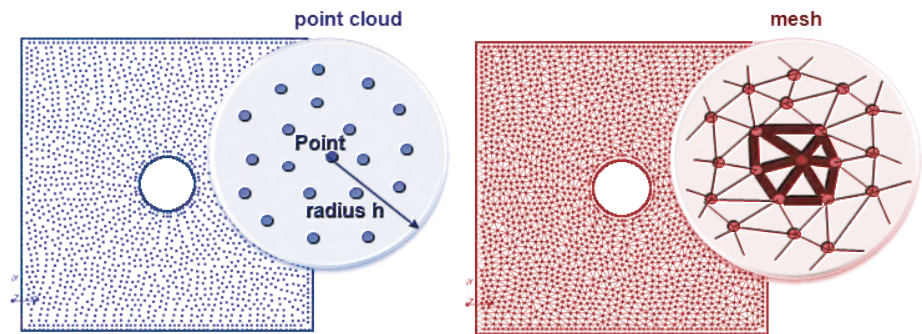
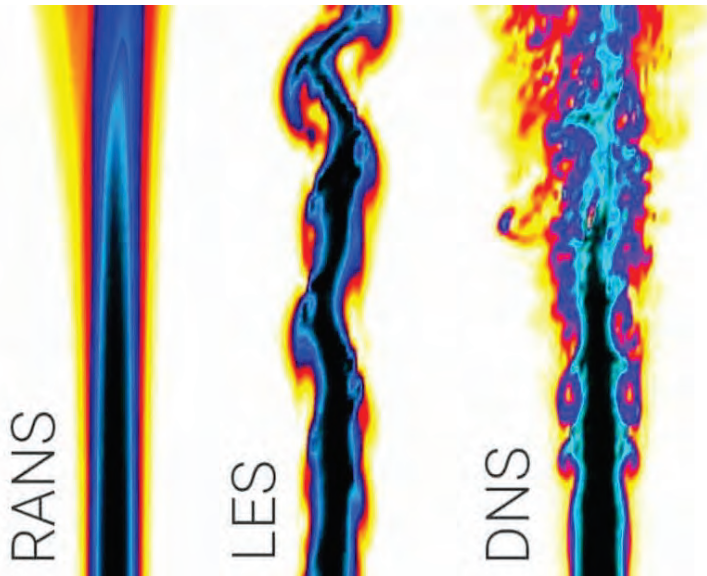
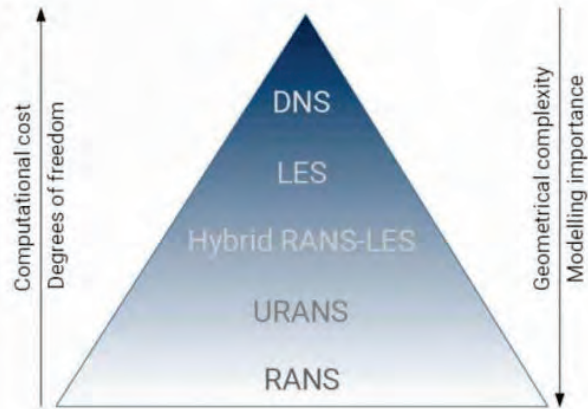
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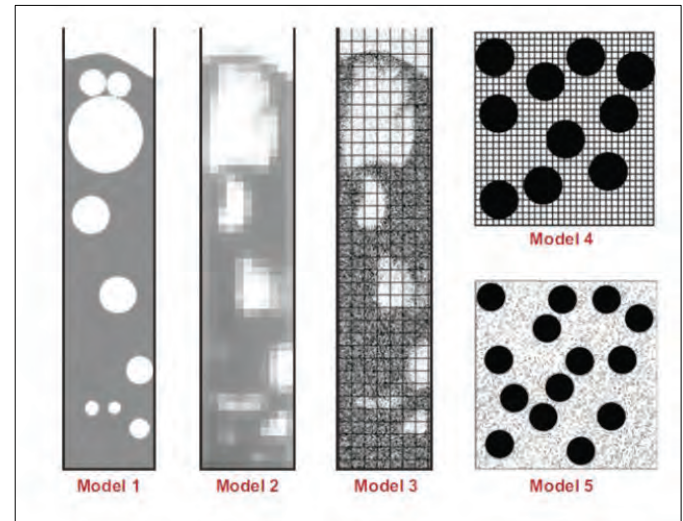
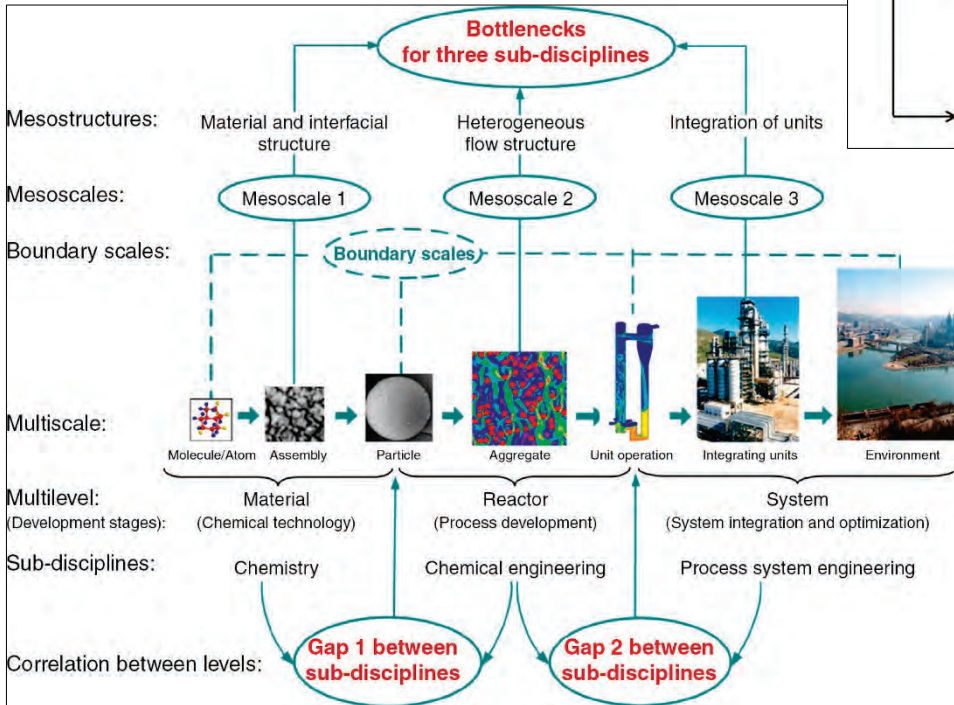
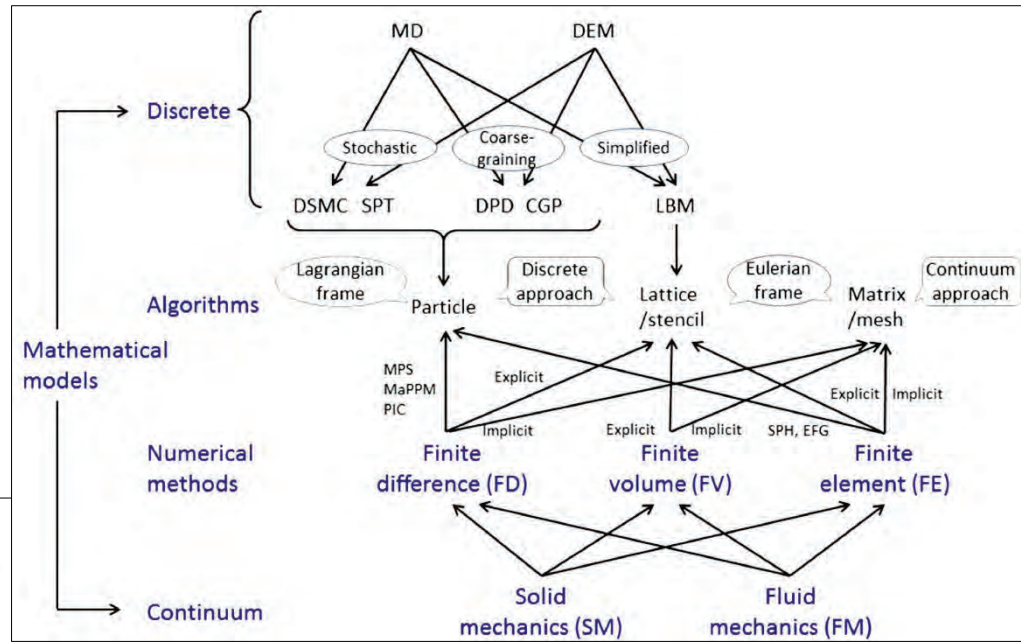
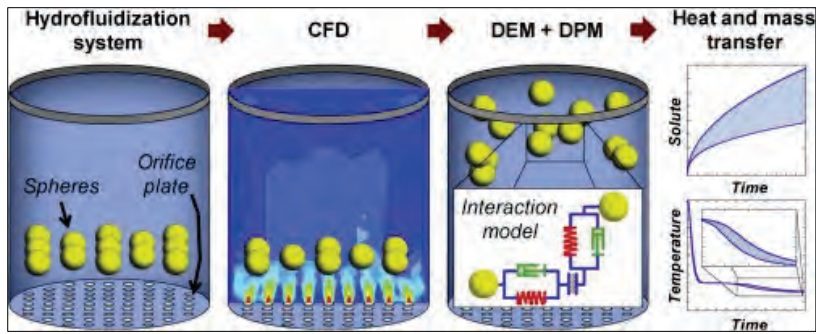
Philip L. Roe



# CFD TODAY (2022)



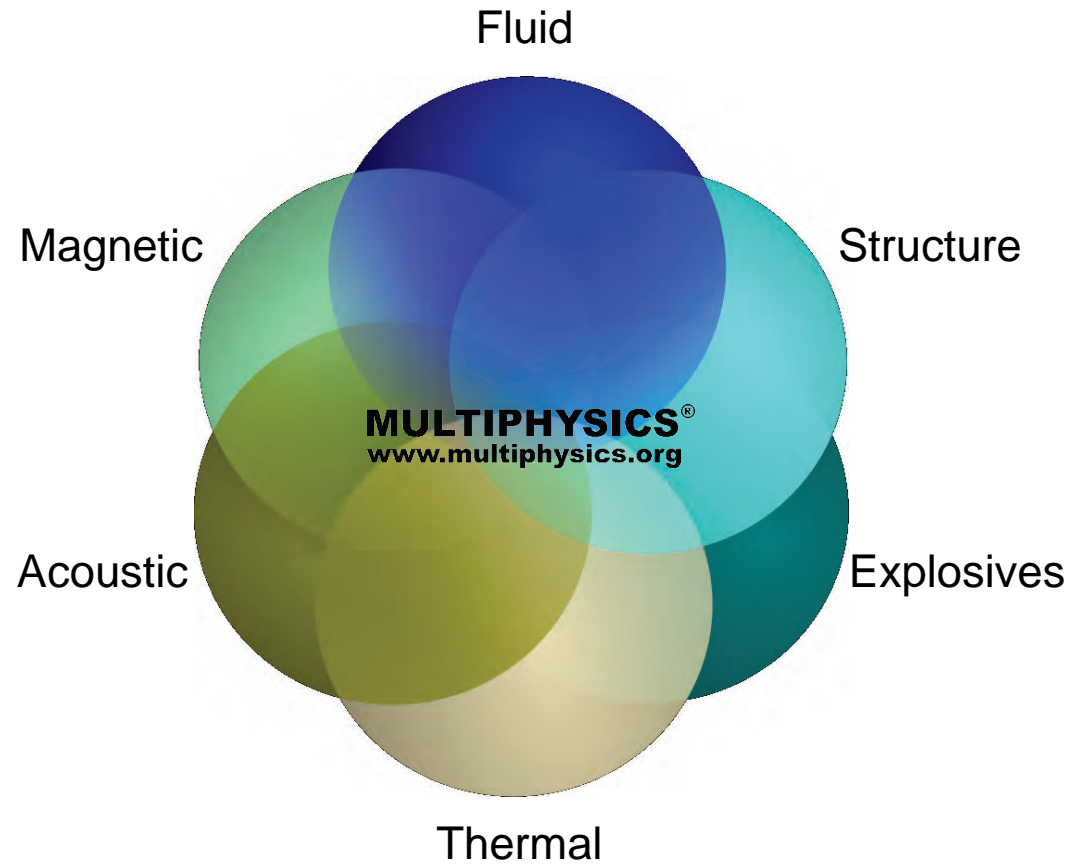
# CFD TODAY (2022) - EXAMPLE



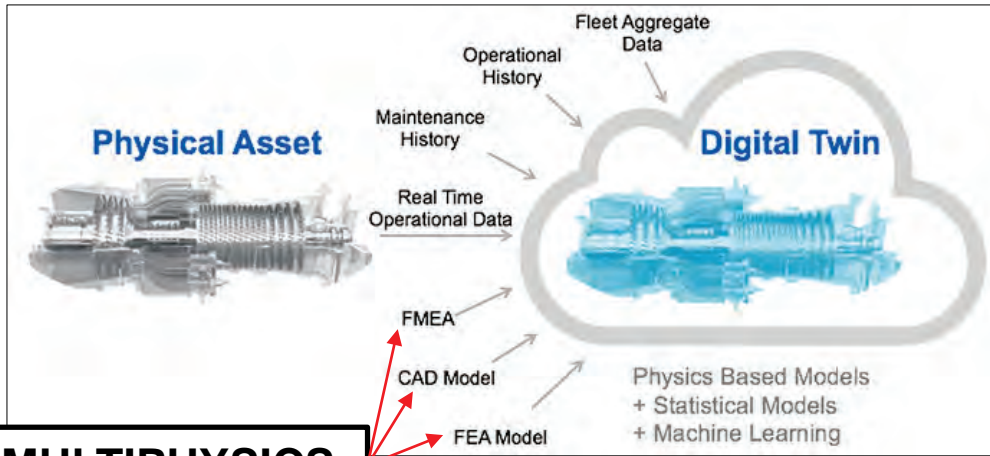
# WHAT'S NEXT?



# FUTURE IS MULTIPHYSICS



# FUTURE IS MULTIPHYSICS



## MULTIPHYSICS

**As Designed**

**MODEL-BASED ENTERPRISE & SYSTEMS ENGINEERING**

**FLUIDS**

**STRUCTURES**

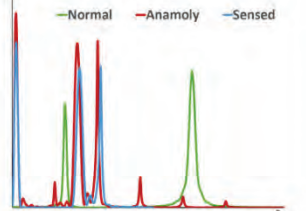
**ELECTRONICS**

**SEMICONDUCTOR**

**EMBEDDED SOFTWARE**

# DIGITAL TWIN

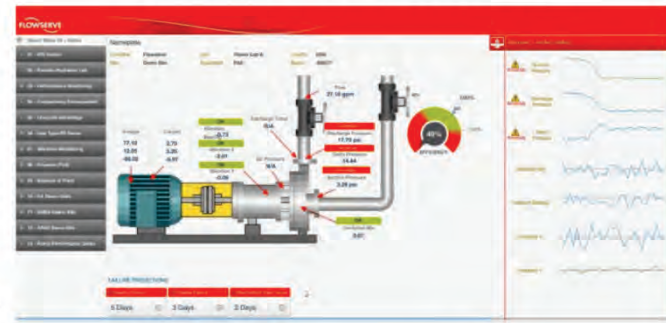
**Digital Signatures**



**Virtual Sensors**

**As Operated**

**INTEGRATED IOT ASSETS & ECOSYSTEMS**



**Assess:**

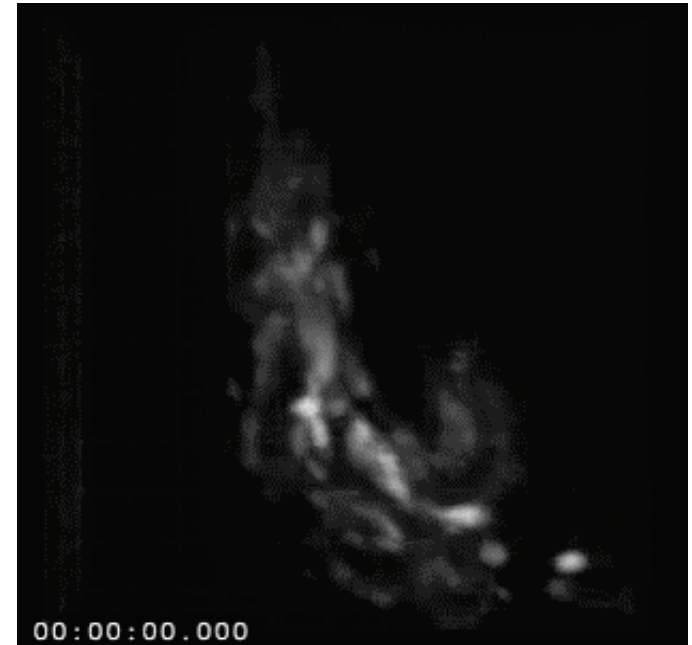
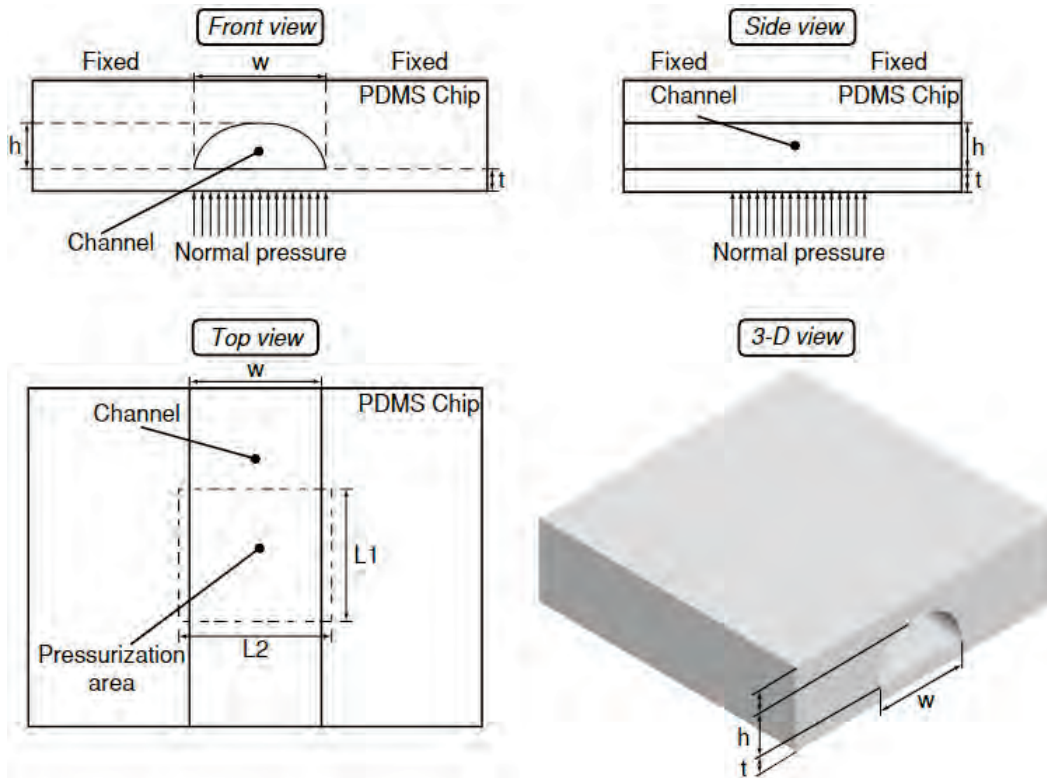
- Performance
- Life / Durability
- Diagnostics
- Optimization

**Further improve:**

- Cost
- Weight
- Efficiency
- Robustness



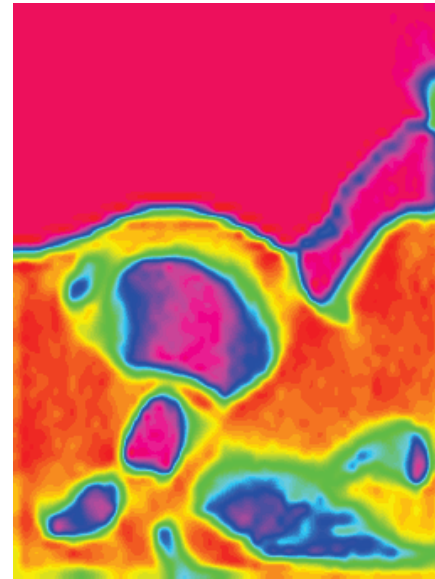
# MICRO-FLUIDIC VALVE



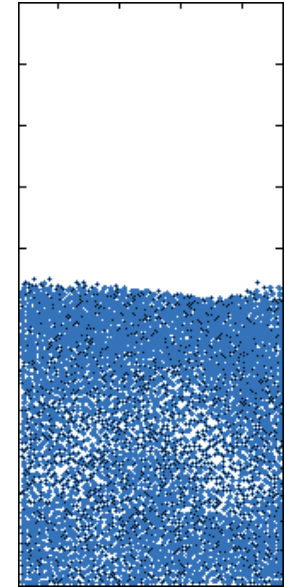
H Khawaja, I Raouf, K Parvez, A Scherer. Optimization of elastomeric micro-fluidic valve dimensions using nonlinear finite element methods. The International Journal of Multiphysics, 2009, 3(2): pp. 187 - 200. <http://dx.doi.org/10.1260/175095409788837847>



# FLUIDIZED BED - BUBBLES

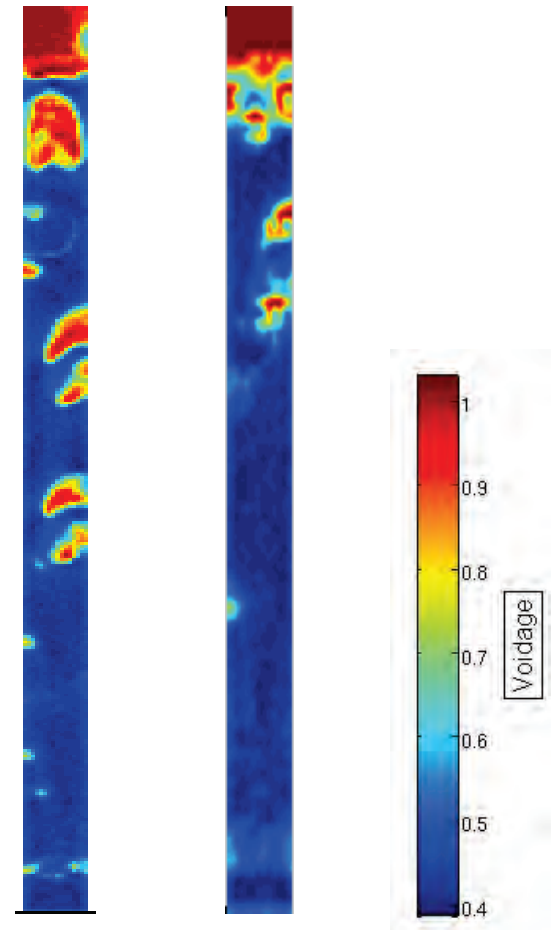
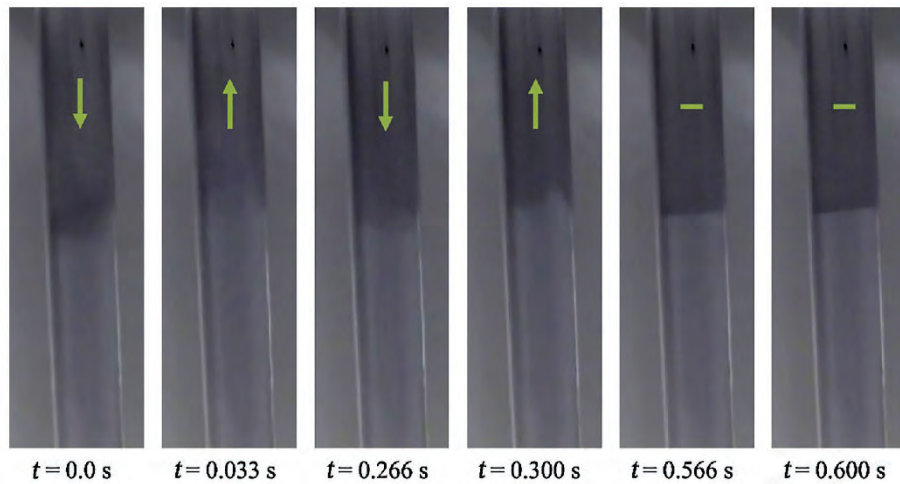


**Fluid Inlet**



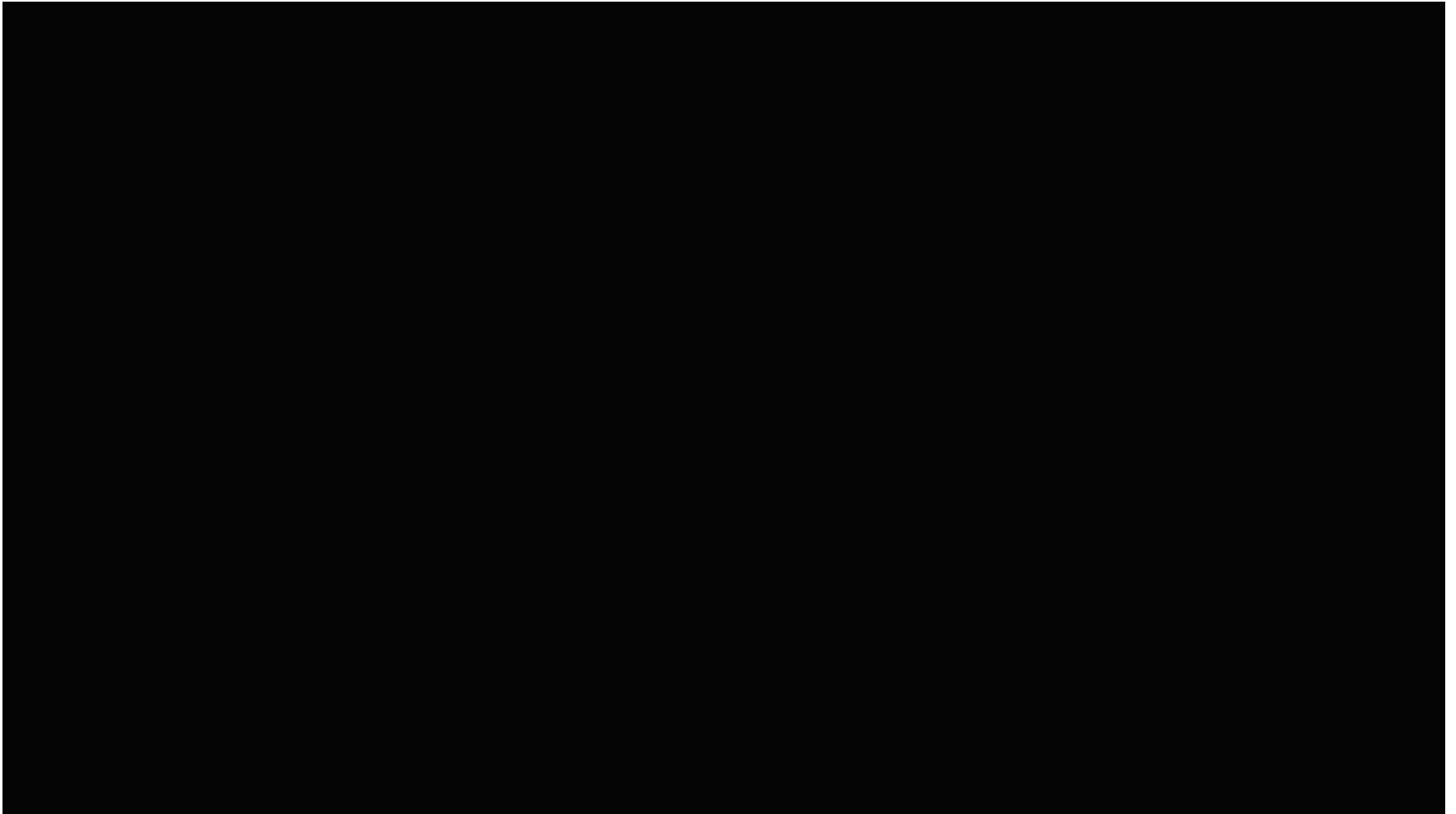
**Fluid Inlet**

# FLUIDIZED BED – SOUND WAVES



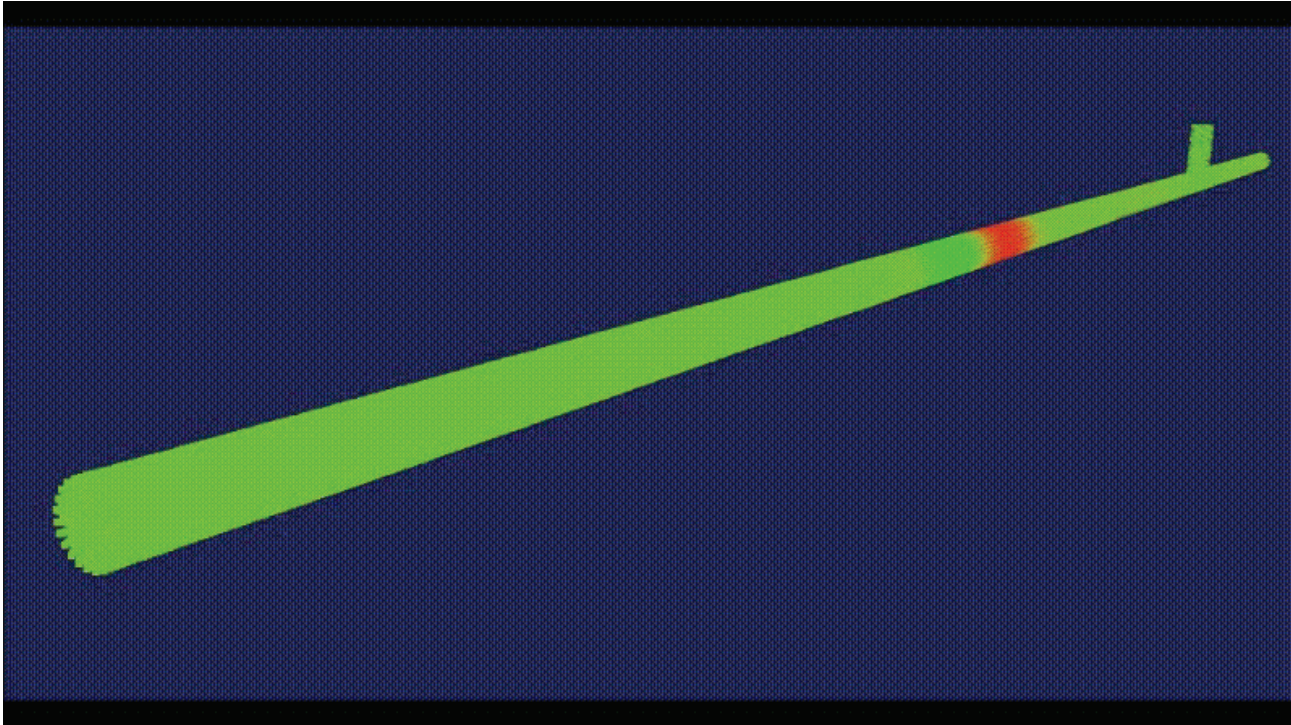
H Khawaja. Study of Sound Waves in Fluidized Bed using CFD-DEM Simulations. Particuology, 2017, 38: pp.126 - 133.  
<https://doi.org/j.partic.2017.07.002>

## SHOCK-TUBE (VIDEO)



H Khawaja et al. Experimental and Numerical Study of Pressure in a Shock Tube. J Press Vess-T ASME, 2016, 138(4): 041301.  
<http://dx.doi.org/10.1115/1.4031591>

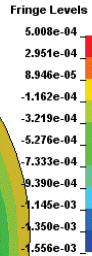
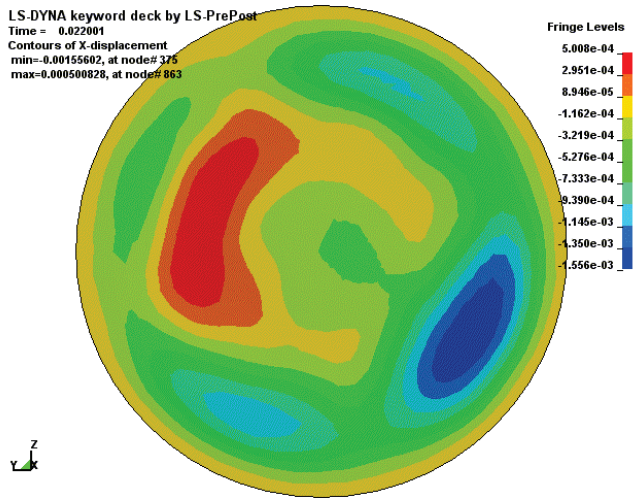
# SHOCK-TUBE



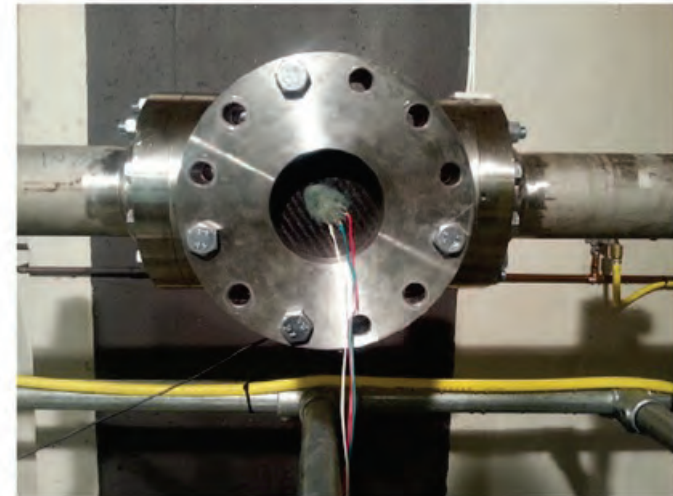
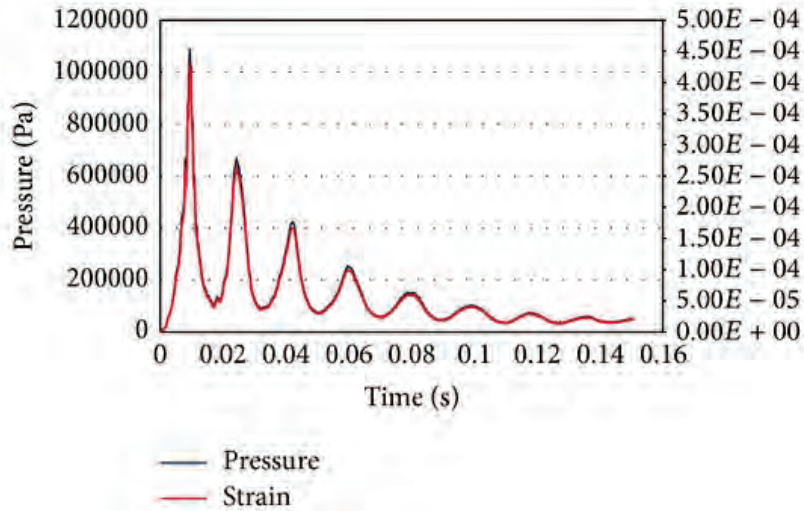
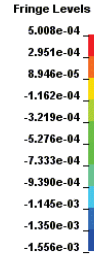
H Khawaja et al. Experimental and Numerical Study of Pressure in a Shock Tube. J Press Vess-T ASME, 2016, 138(4): 041301.  
<http://dx.doi.org/10.1115/1.4031591>

# CFRP DYNAMIC RESPONSE

LS-DYNA keyword deck by LS-PrePost  
Time = 0.022001  
Contours of X-displacement  
min=-0.00155602, at node# 375  
max=0.000500828, at node# 863

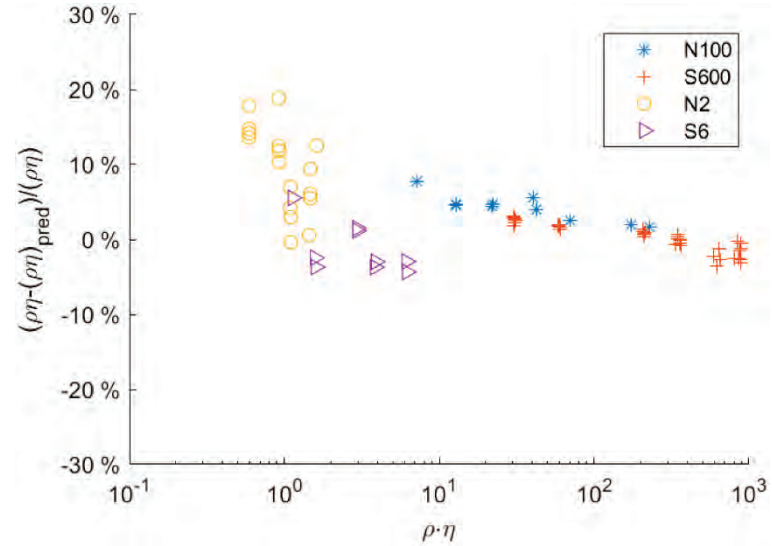
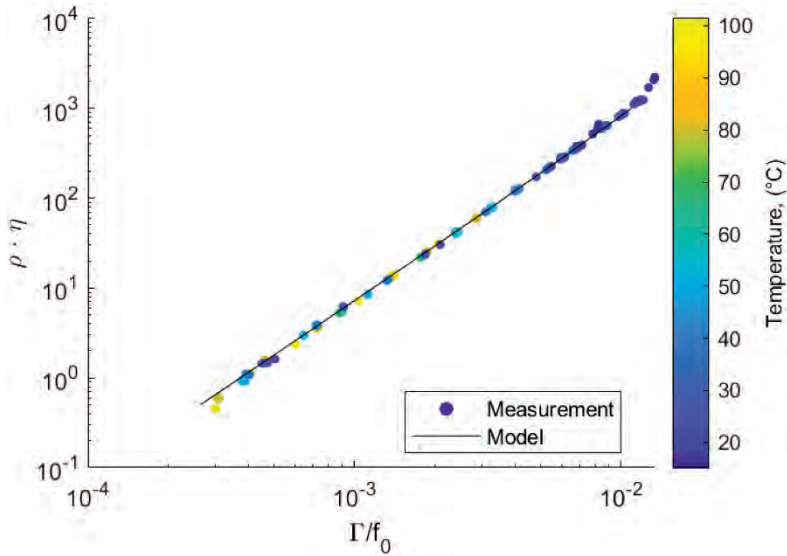


LS-DYNA keyword deck by LS-PrePost  
Time = 0.022001  
Contours of X-displacement  
min=-0.00155602, at node# 375  
max=0.000500828, at node# 863



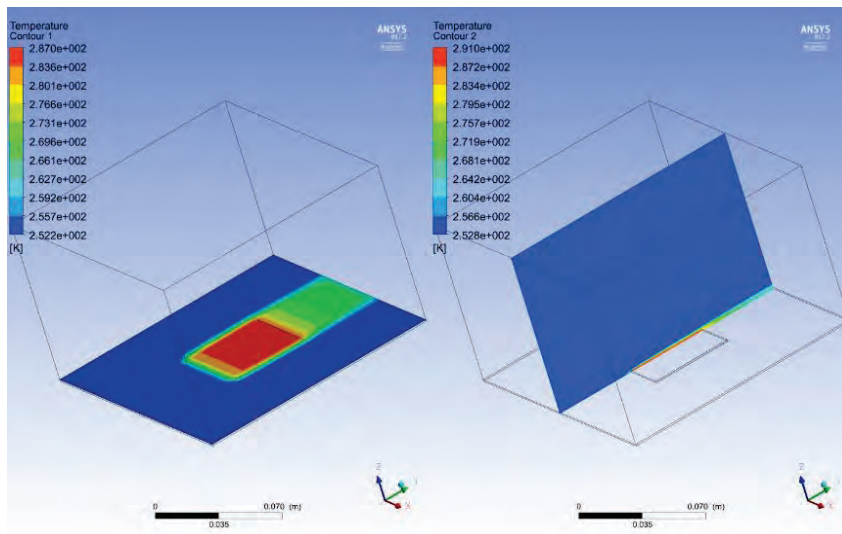
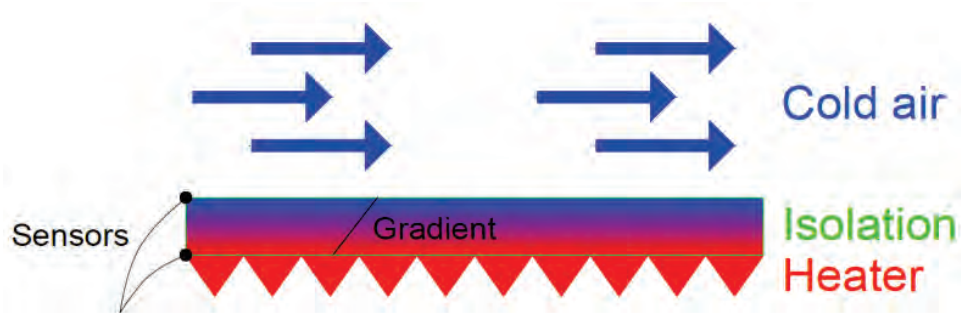
H Khawaja et al. Study of CFRP Shell Structures under Dynamic Loading in Shock Tube Setup. Journal of Structures, 2014. <http://dx.doi.org/10.1155/2014/487809>

# FLUID VISCOSITY-DENSITY SENSOR



Daniel Brunner, Joe Goodbeard, Klaus Hausler, Sunil Kumar, Gernot Boiger, Hassan Khawaja. Analysis of a Tubular Torsionally Resonating Viscosity–Density Sensor. Sensors, 2020, 20(11). <http://dx.doi.org/10.3390/s20113036>

# ENVIRONMENT EXPOSURE SENSOR

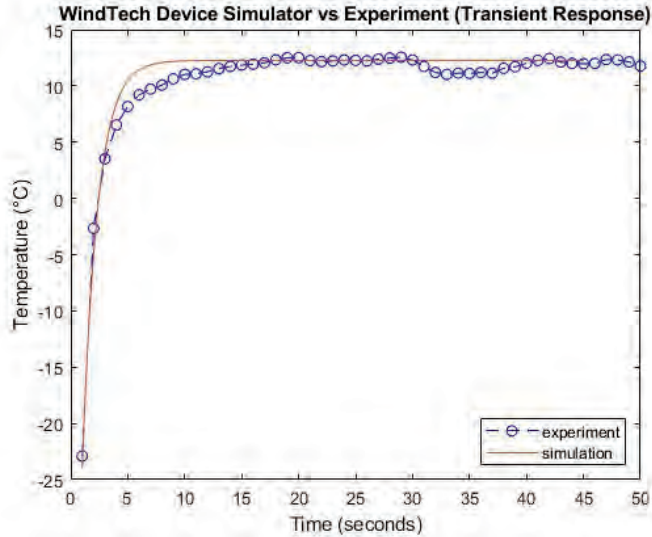


# ENVIRONMENT EXPOSURE SENSOR

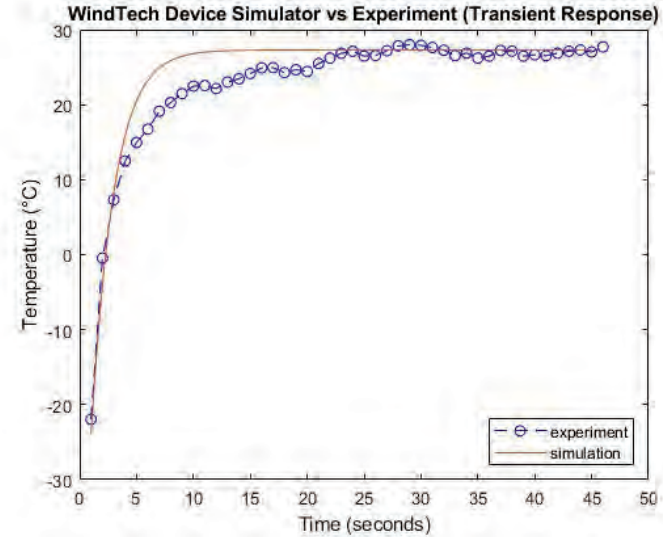
Temperature = -23°C, Relative Humidity = 72%

Wind Velocity = 8 m/s

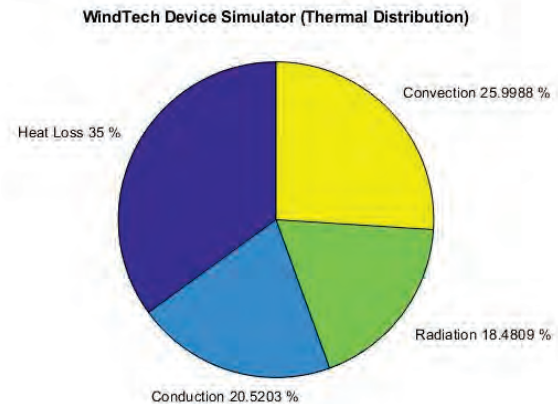
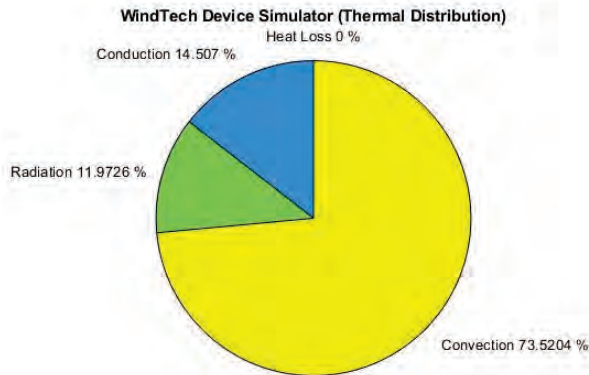
Wind Velocity = 0.5 m/s



Heated Temperature = 12.1°C

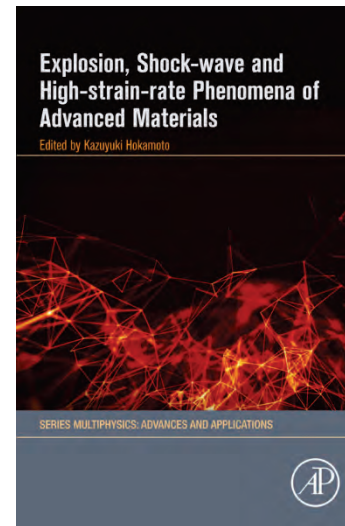
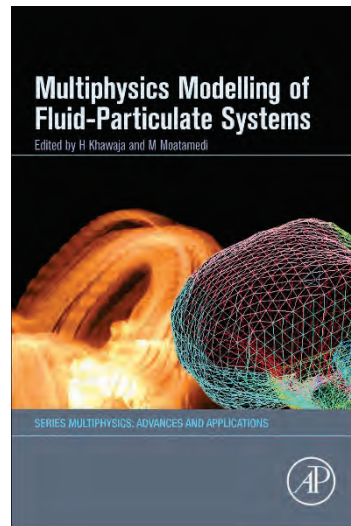
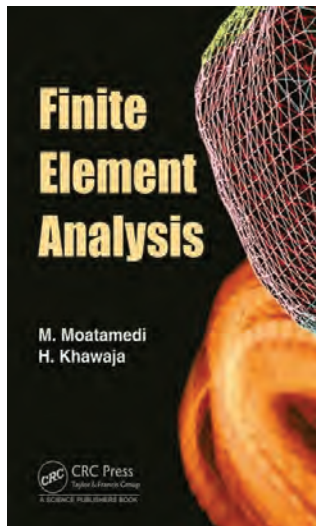


Heated Temperature = 26.9°C





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## QUESTIONS/COMMENTS



## CONTACT

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