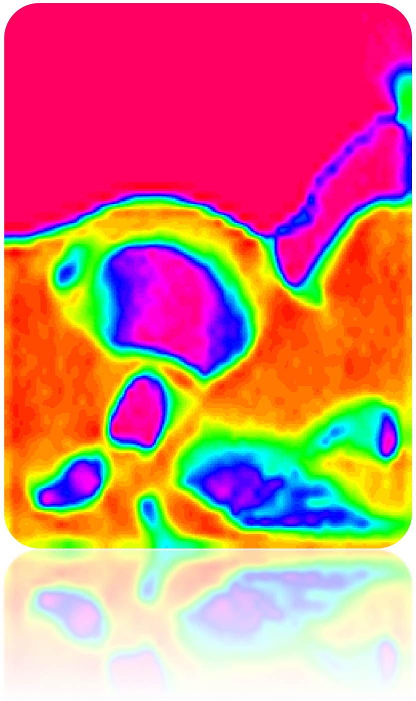
COMPUTATIONAL FLUID DYNAMICS - A STEPPING-STONE OF MULTIPHYSICS



H KHAWAJA, IAP FAGDAG MED PRESENTASJON AV FORSKNINGSAKTIVITETER, 23 NOV 2022

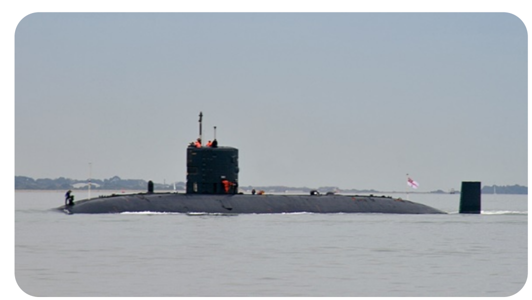
PRESENTATION OVERVIEW

- INTRODUCTION
  - Presenter's Bio

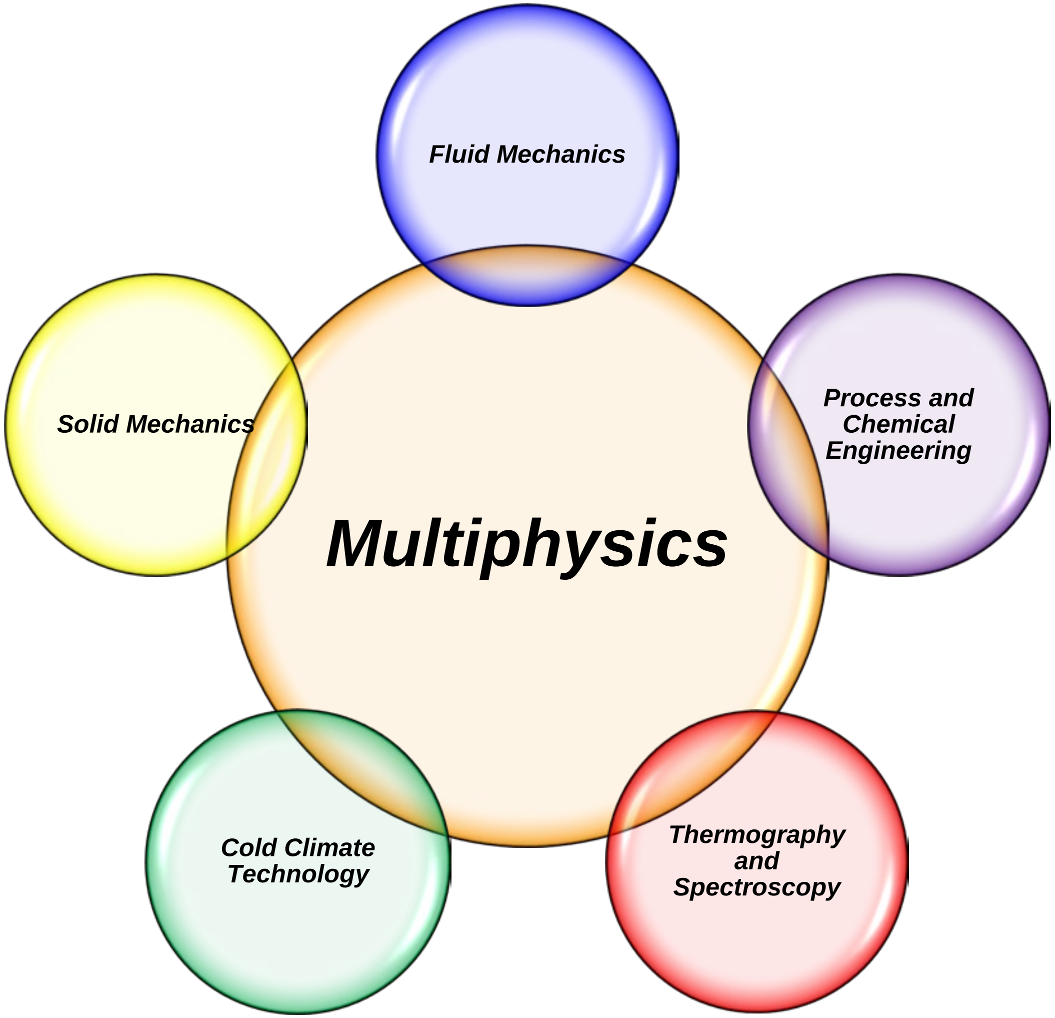
- HISTORICAL PRESPECTIVE
  - Evolution of Fluid Mechanics
  - Computational Fluid Dynamics (CFD)
  - Semi-Implicit Pressure Linked Equation (SIMPLE)
  - Words of Caution | Colorful Fluid Dynamics | CFD Today
  - Future is Multiphysics

- PROJECT EXAMPLES
  - Micro-Fluidic Valve (NUST, CALTECT)
  - Fluidized Bed (CAMBRIDGE, ETH ZURICH)
  - Shock-Tube (NARVIK, LILLE)
  - Fluid Viscosity-Density Sensor (INNOSUISSE, RHEONICS, ZHAW)
  - Environment Exposure Sensor (WINDTECH, UIT)
  - Few Others

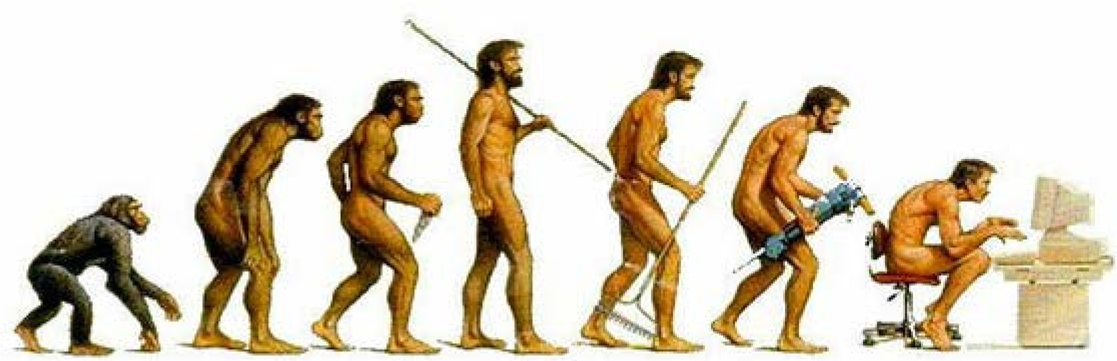
Presenter's Bio



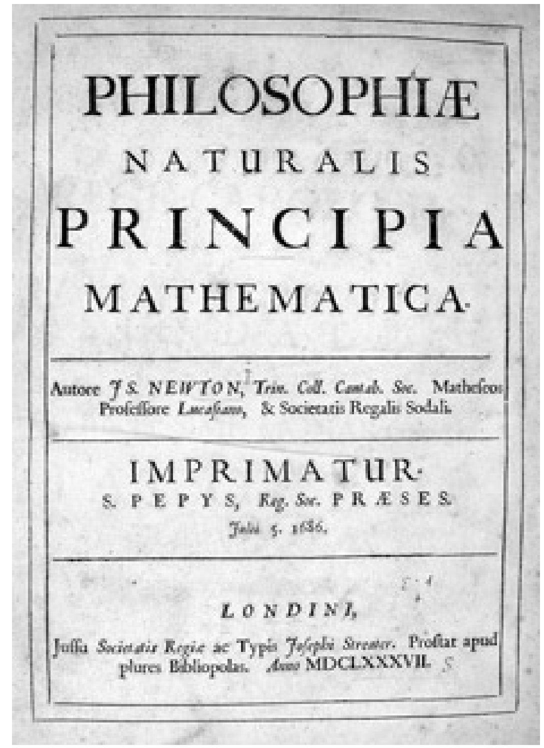
PRESENTER'S BIO


Fluid Mechanics
Solid Mechanics
Process and Chemical Engineering
Multiphysics
Cold Climate Technology
Thermography and Spectroscopy

EVOLUTION OF FLUID MECHANICS (HISTORICAL PRESPECTIVE)



Newton (1686)	Bernoulli (1738)	Euler (1757)	Navier (1822)	Stokes (1845)	CFD* (1922)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

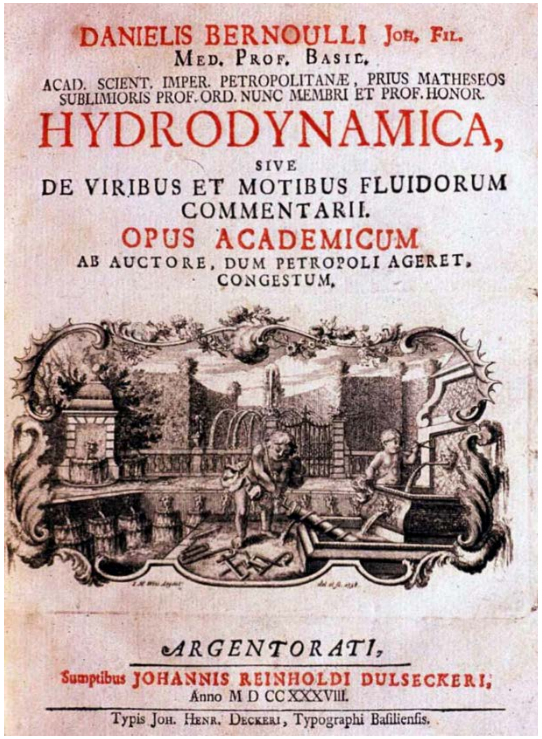
Autore J S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

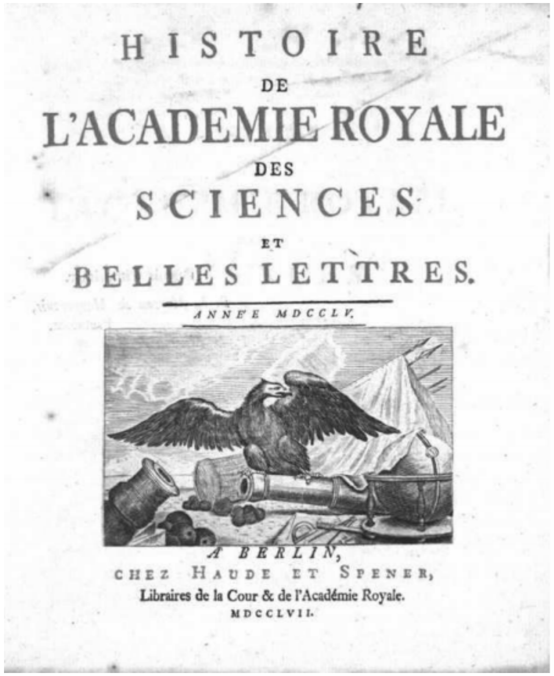
LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

$$F = ma$$

BERNOULLI (1738)



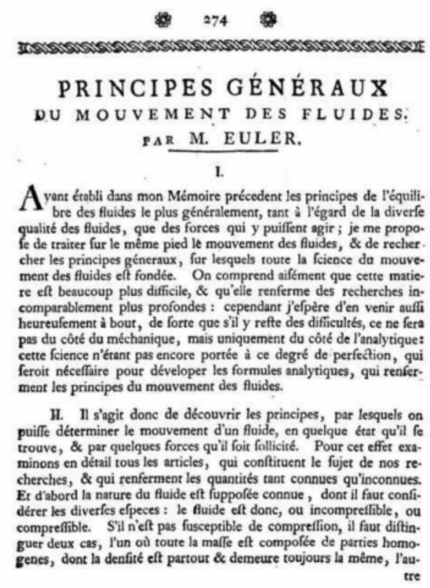
$$p_0 + \frac{1}{2}\rho v_0^2 + \rho g h_0 = constant$$



HISTOIRE
DE
L'ACADEMIE ROYALE
DES
SCIENCES
ET
BELLES LETTRES.

ANNÉE MDCCLV.

A BERLIN,
CHEZ HAUDE ET SPENER,
Libraires de la Cour & de l'Académie Royale.
MDCCLVII.



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PRINCIPES GÉNÉRAUX
DU MOUVEMENT DES FLUIDES.
PAR M. EULER.

I.

Ayant établi dans mon Mémoire précedent 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 lè mouvement des fluides, & de rechercher les principes generaux, ſur lesquels toute la ſcience du mouvement des fluides eſt fondée. On comprend aiſément que cette matiere 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 méchanique, mais uniquement du côté de l'analytique: cette ſcience n'étant pas encore portée à ce degré de perfection, qui feroit néceſſaire pour développer les formules analytiques, qui renferment les principes du mouvement des fluides.

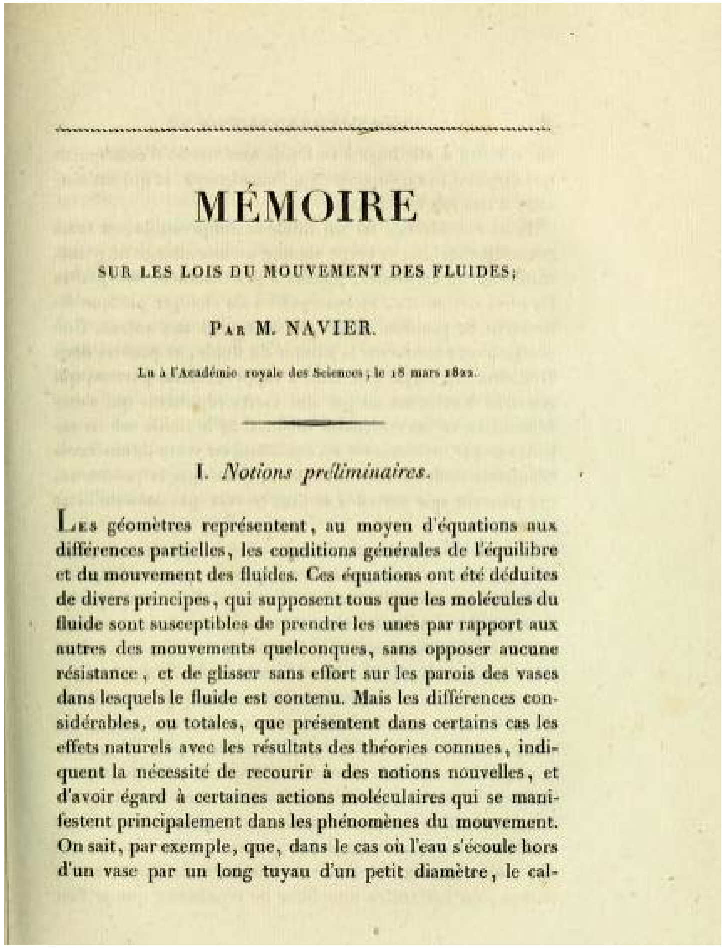
II. Il s'agit donc de découvrir les principes, par lesquels on puiſſe déterminer le mouvement d'un fluide, en quelque état qu'il ſe trouve, & par quelques forces qu'il ſoit ſollicité. Pour cet effet examinons en détail tous les articles, qui conſtituent le ſujet de nos recherches, & qui renferment les quantités tant connues qu'inconnues. Et d'abord la nature du fluide eſt ſuppoſée connue, dont il faut conſidérer les diverſes eſpeces : 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 homogenes, dont la denſité eſt partout & demeure toujours la même, l'autre

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{u}) = 0$$

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

$$\frac{\partial E}{\partial t} + \nabla.(\mathbf{u}\,(E + p)) = 0$$

NAVIER (1822)



MÉMOIRE

SUR LES LOIS DU MOUVEMENT DES FLUIDES;

PAR M. NAVIER.

Lu à l'Académie royale des Sciences; le 18 mars 1822.

I. *Notions préliminaires.*

Les géomètres représentent, au moyen d'équations aux différences partielles, les conditions générales de l'équilibre et du mouvement des fluides. Ces équations ont été déduites de divers principes, qui supposent tous que les molécules du fluide sont susceptibles de prendre les unes par rapport aux autres des mouvements quelconques, sans opposer aucune résistance, et de glisser sans effort sur les parois des vases dans lesquels le fluide est contenu. Mais les différences considérables, ou totales, que présentent dans certains cas les effets naturels avec les résultats des théories connues, indiquent la nécessité de recourir à des notions nouvelles, et d'avoir égard à certaines actions moléculaires qui se manifestent principalement dans les phénomènes du mouvement. On sait, par exemple, que, dans le cas où l'eau s'écoule hors d'un vase par un long tuyau d'un petit diamètre, le cal-

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

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. [8]
Reprinted in Mathematical and Physical Papers, Sir George Gabriel Stokes and Sir J. Larmor, Vol. 3, 1880-1905]

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 result 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 be 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 shewn 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 viscidity in liquids, of resistance to the motion of bodies passing through them, independently of their density ? a property, in such case,

1

$$\rho \frac{D\boldsymbol{u}}{Dt} = -\nabla p + \nabla . \boldsymbol{\tau} + \rho \boldsymbol{g}$$

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)

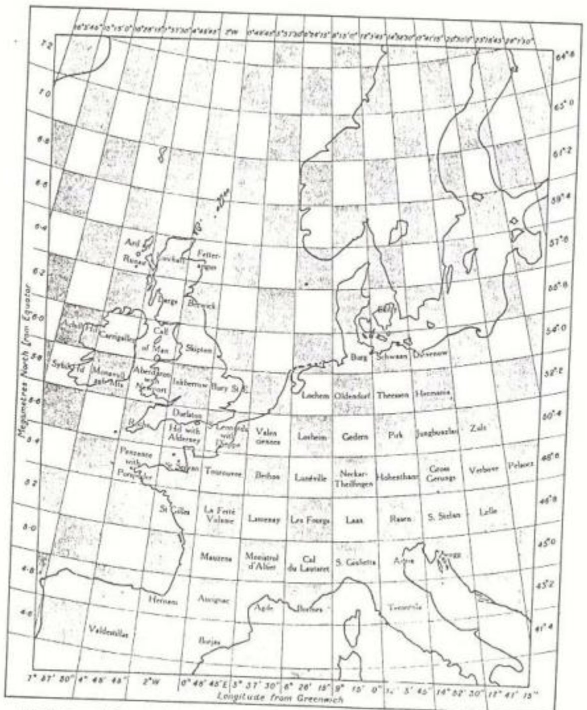
NOTABLE OTHERS (FLUID MECHANICS)

- 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 here disregarded. Pressure to be observed at the centre of each shaded chequer, velocity at the centre of each white chequer. 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 "St Leonards with 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 ESKDALEMUIR OBSERVATORY

LECTURER ON PHYSICS AT WESTMINSTER TRAINING COLLEGE

$\Delta t = 12, 24h$

$\Delta p = 150mb$!

numerically unstable !

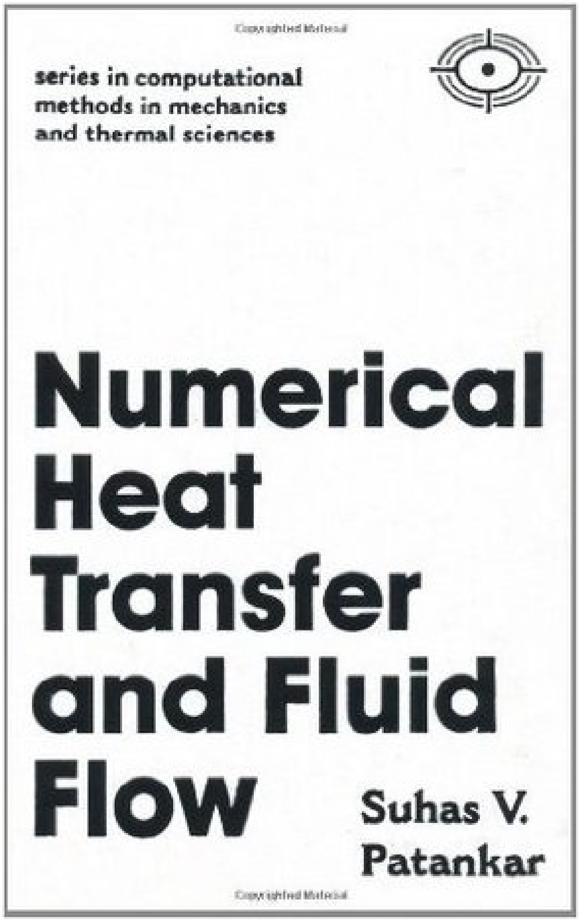
L.F. Richardson (1922)
Weather Prediction by Numerical Process,
Cambridge University Press

CAMBRIDGE
AT THE UNIVERSITY PRESS
1922

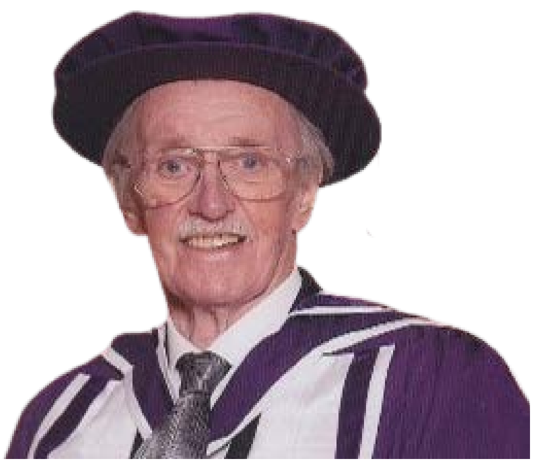
19

Lewis Fry Richardson
(1881 – 1953)

Semi-Implicit Pressure Linked Equation (1979)



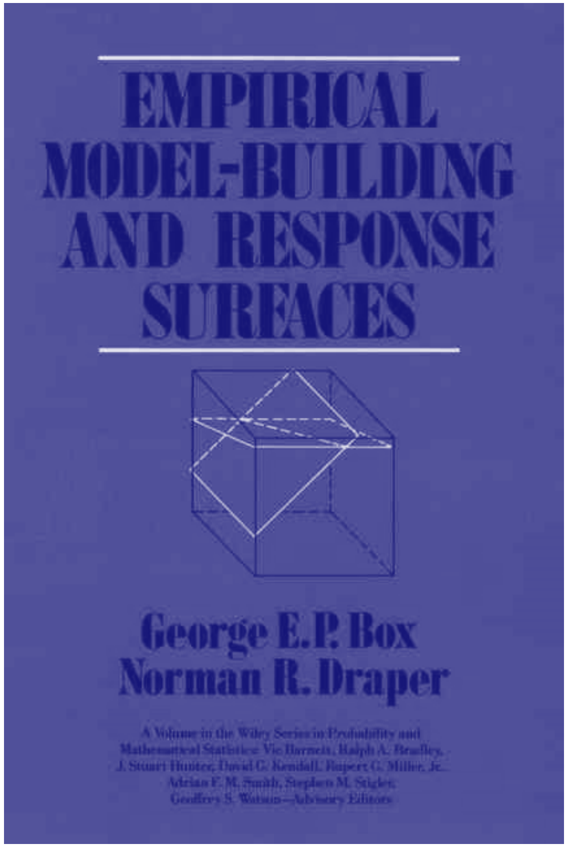
Shuhas V. Patankar
(1941-)



Dudley Brian Spalding
(1923 – 2016)

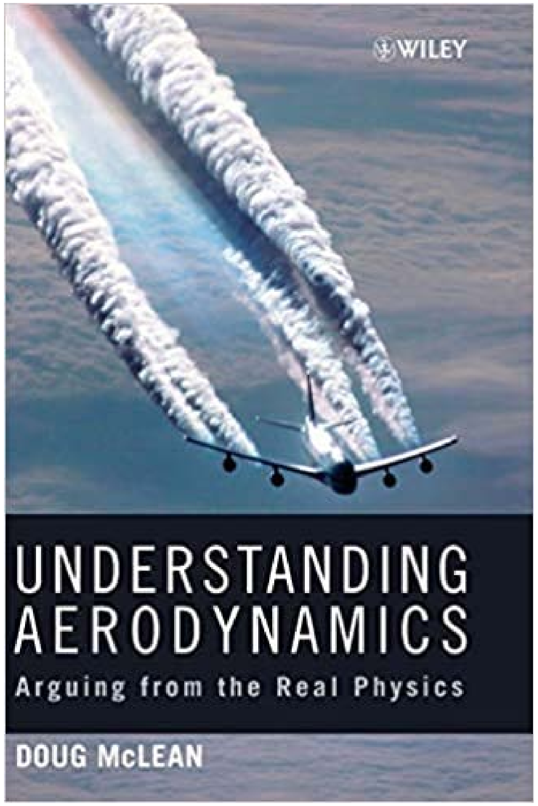
"Essentially, all models are wrong, but some are useful,"

"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)

"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)

Common Misconceptions in Aerodynamics, Lecture: https://www.youtube.com/watch?v=QKCK4lJLQHU

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

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

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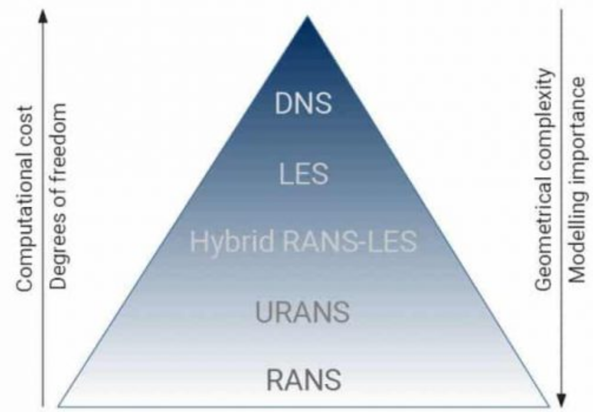
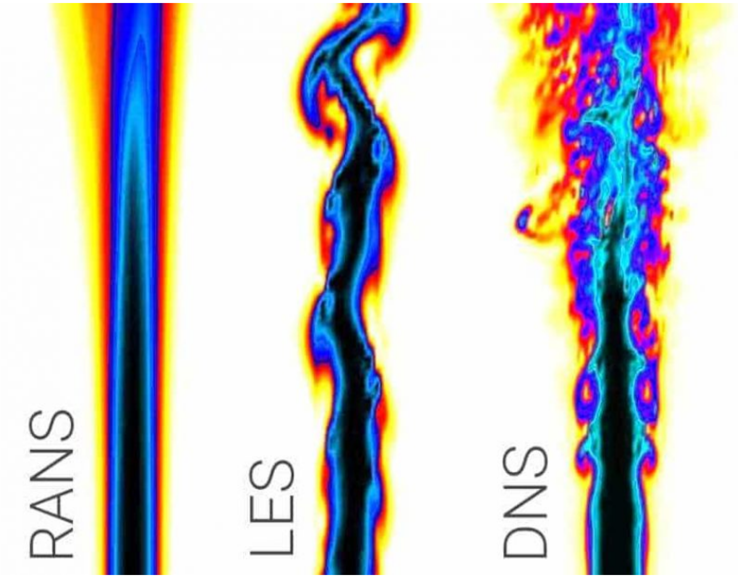
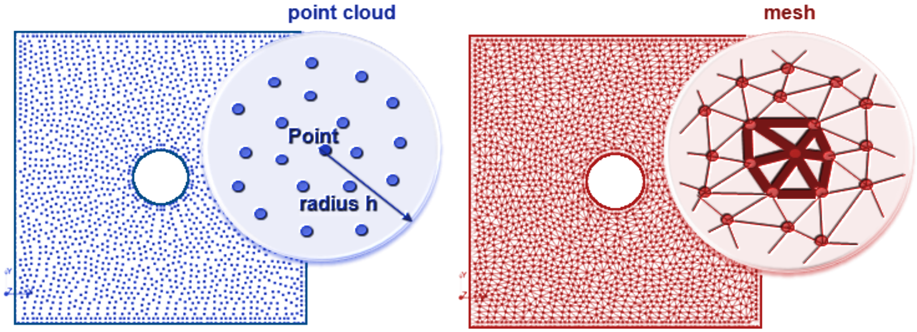
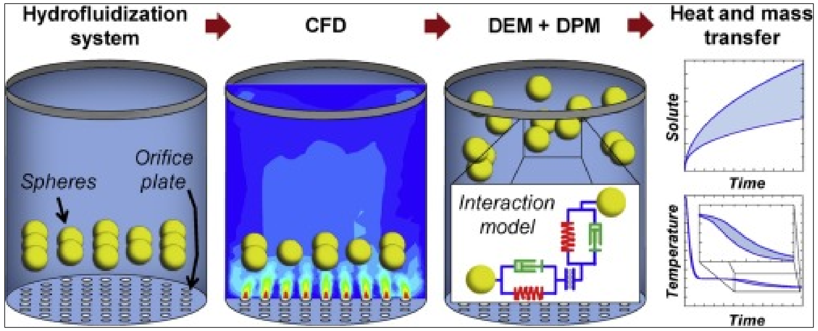
0021-9991/81/100357-16$02.00/0

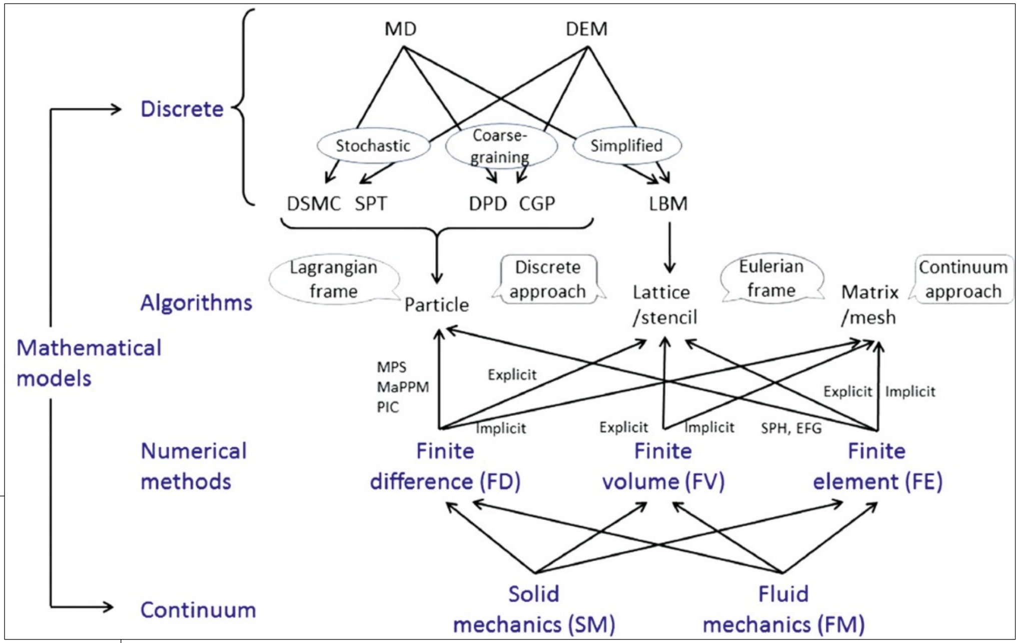
Philip L. Roe

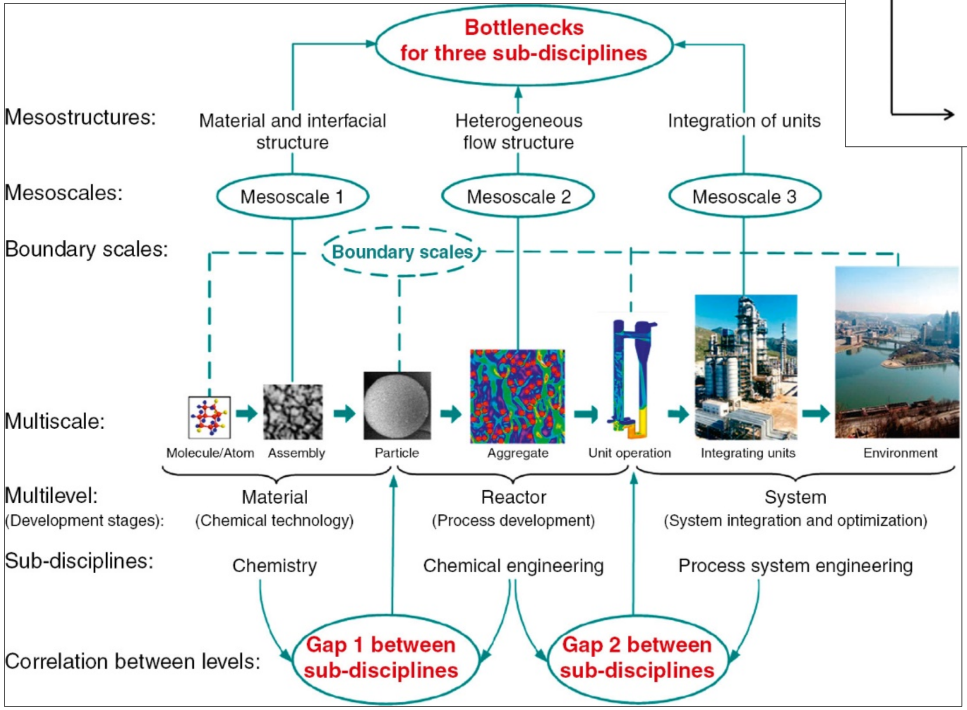

DNS
LES
Hybrid RANS-LES
URANS
RANS
Computational cost
Degrees of freedom
Geometrical complexity
Modelling importance

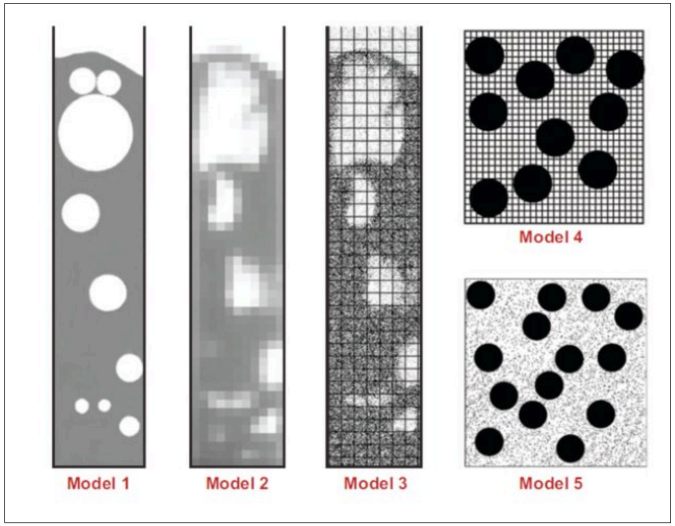

RANS
LES
DNS


point cloud
Point
radius h
mesh


Hydrofluidization system
CFD
DEM + DPM
Heat and mass transfer
Spheres
Orifice plate
Interaction model
Solute
Time
Temperature
Time

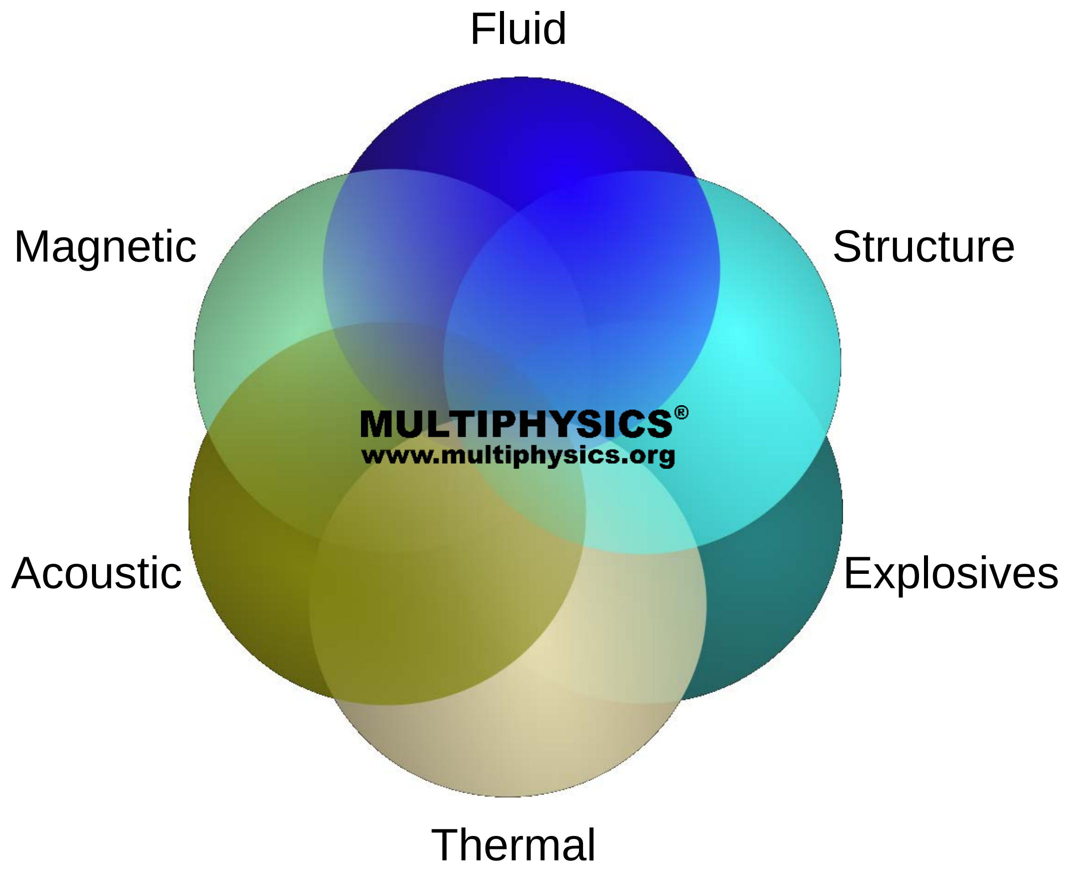

MD
DEM
Discrete
Stochastic
Coarse-graining
Simplified
DSMC SPT
DPD CGP
LBM
Lagrangian frame
Discrete approach
Eulerian frame
Continuum approach
Algorithms
Particle
Lattice /stencil
Matrix /mesh
Mathematical models
MPS
MaPPM
PIC
Explicit
Implicit
Explicit
Implicit
Explicit
Implicit
SPH, EFG
Numerical methods
Finite difference (FD)
Finite volume (FV)
Finite element (FE)
Solid mechanics (SM)
Fluid mechanics (FM)
Continuum


Bottlenecks for three sub-disciplines
Mesostructures:
Material and interfacial structure
Heterogeneous flow structure
Integration of units
Mesoscales:
Mesoscale 1
Mesoscale 2
Mesoscale 3
Boundary scales:
Boundary scales
Multiscale:
Molecule/Atom
Assembly
Particle
Aggregate
Unit operation
Integrating units
Environment
Multilevel:
(Development stages):
Material
(Chemical technology)
Reactor
(Process development)
System
(System integration and optimization)
Sub-disciplines:
Chemistry
Chemical engineering
Process system engineering
Correlation between levels:
Gap 1 between sub-disciplines
Gap 2 between sub-disciplines

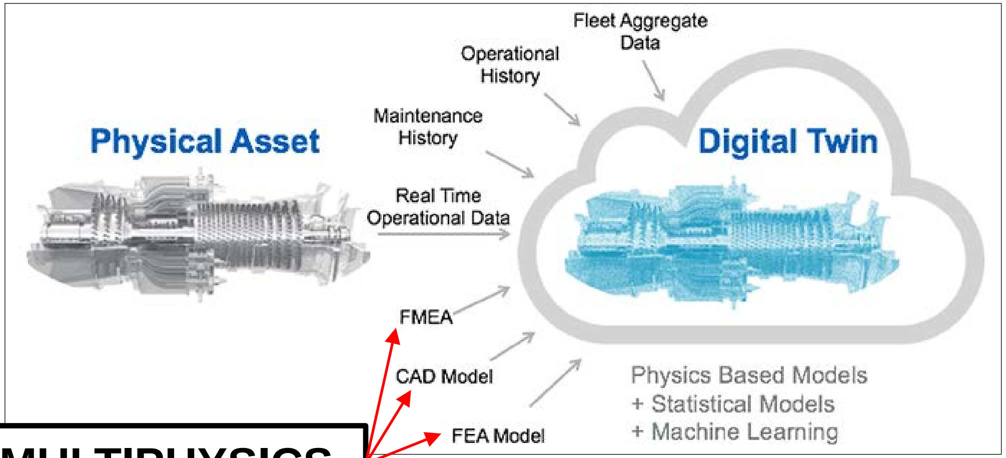

Model 1
Model 2
Model 3
Model 4
Model 5

What's Next?

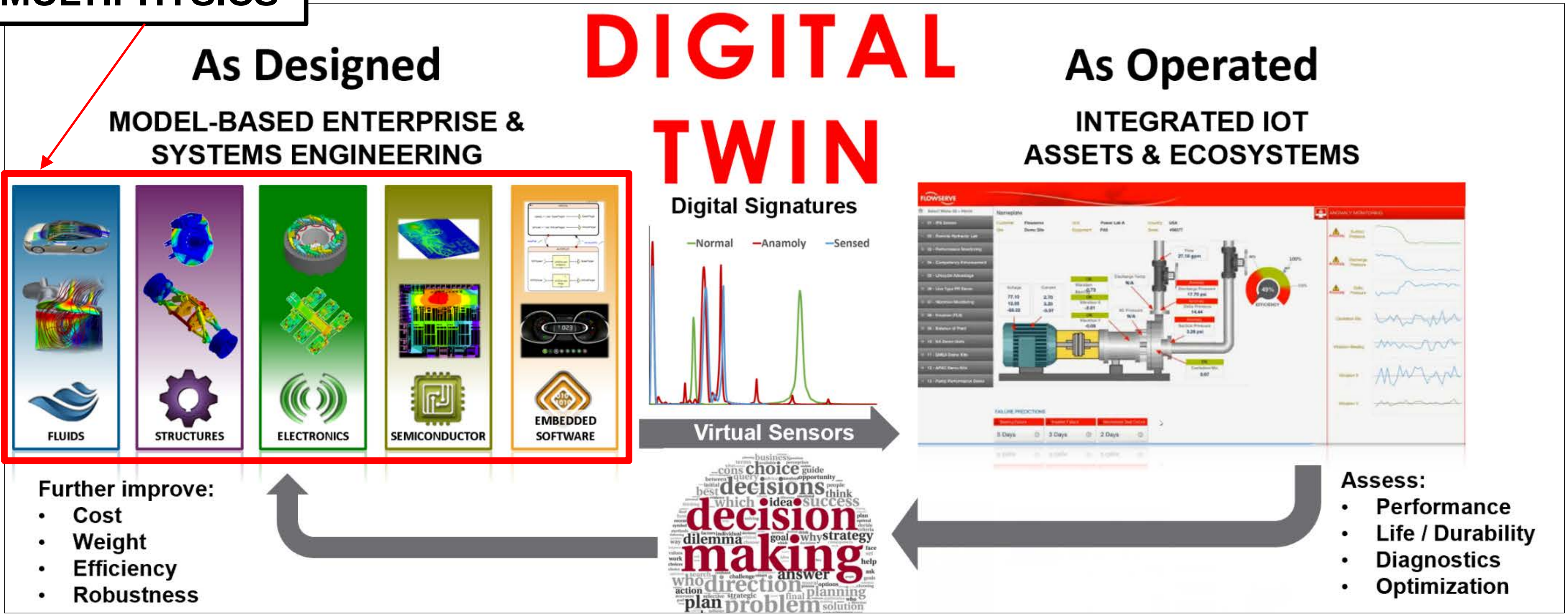
FUTURE IS MULTIPHYSICS

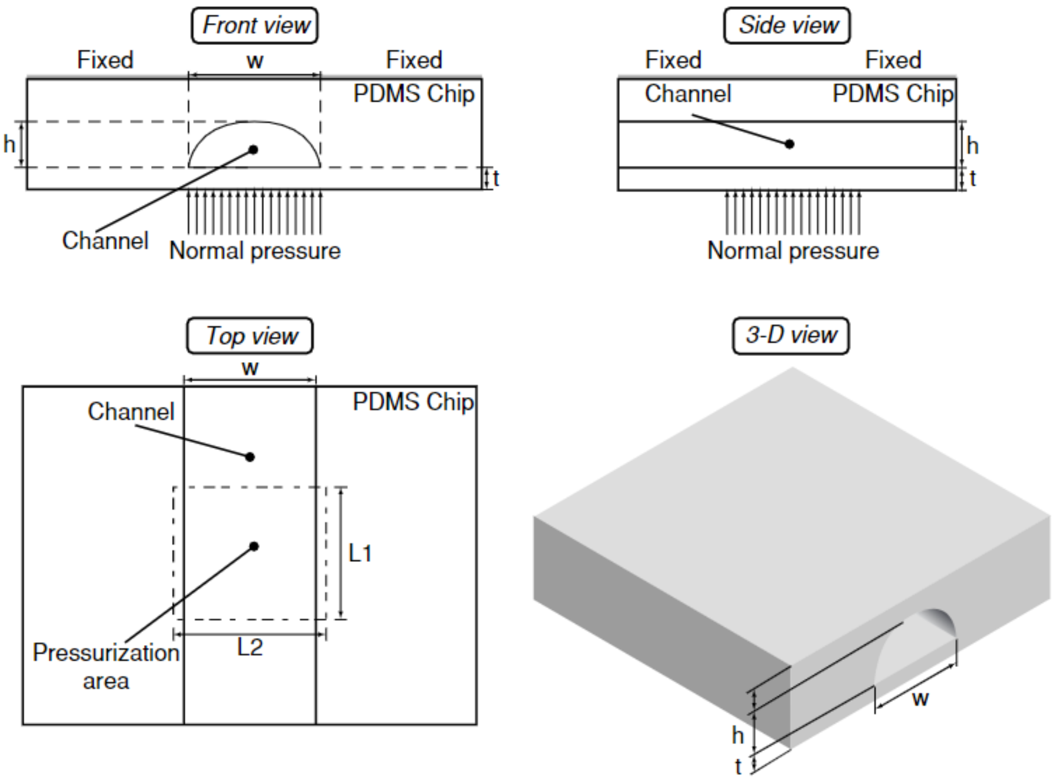


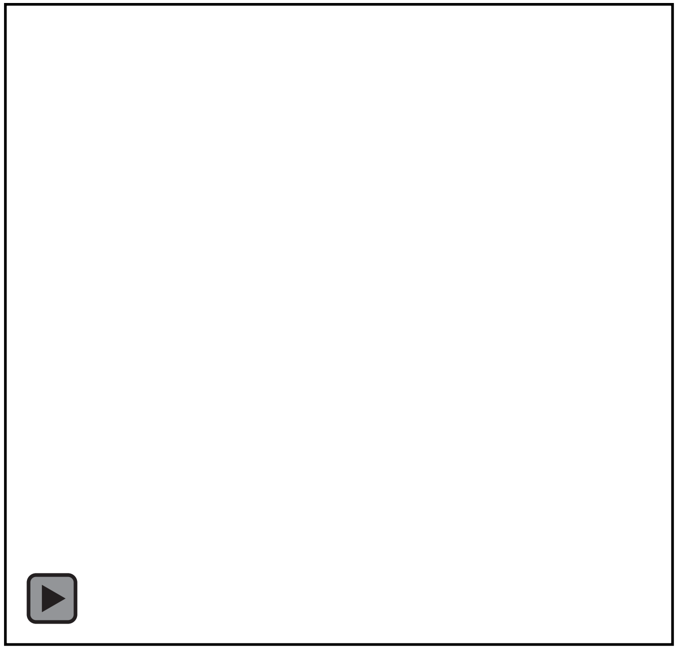
FUTURE IS MULTIPHYSICS



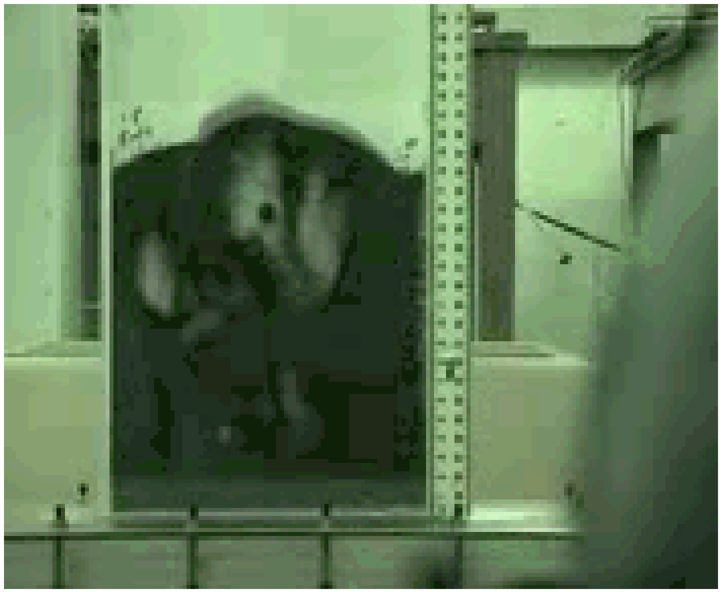
MULTIPHYSICS

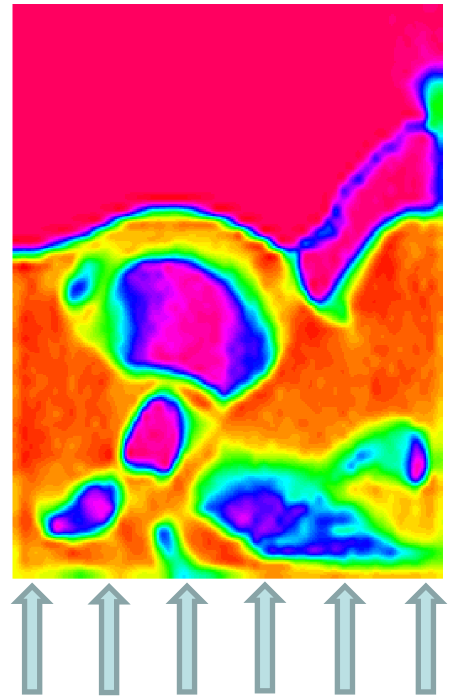




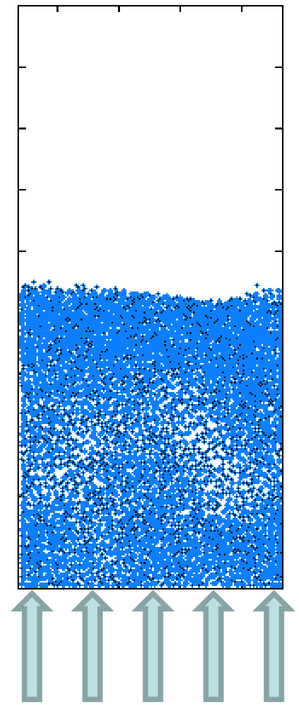


H Khawaja, I Raouf, K Parvez, A Scherer. Optimization of elastomeric micro-fluidic valve dimensions using nonlinear finite element methods. The International Journal of Multiphysics, 2009, 3(2): pp. 187 - 200. http://dx.doi.org/10.1260/175095409788837847





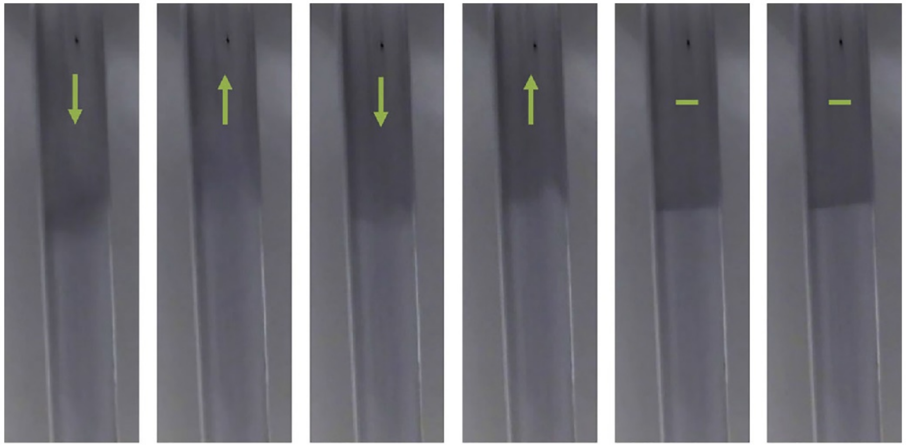
Fluid Inlet

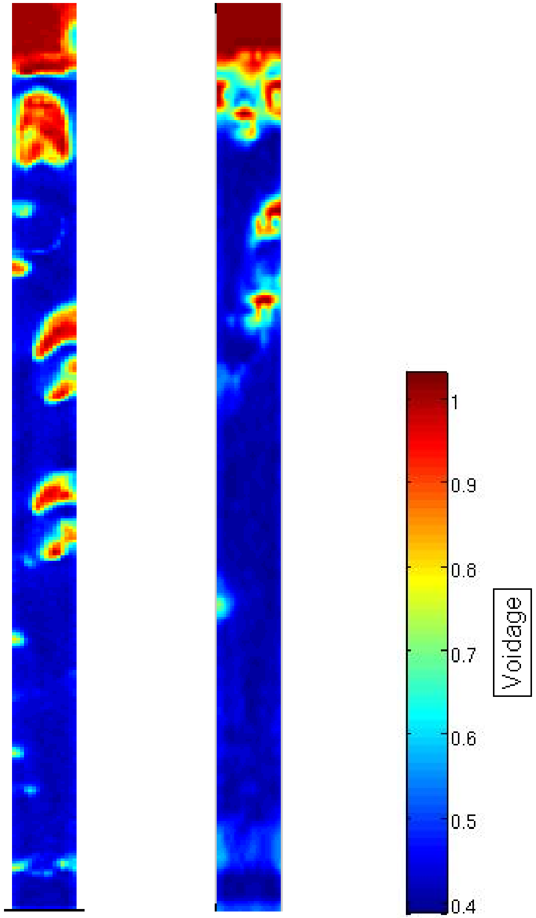


Fluid Inlet

H Khawaja, M Moatamedi. Multiphysics Modelling of Fluid-Particulate Systems. Academic Press, 2020, ISBN 978-0-1281-8345-8.
https://doi.org/10.1016/C2018-0-02737-1

FLUIDIZED BED – SOUND WAVES

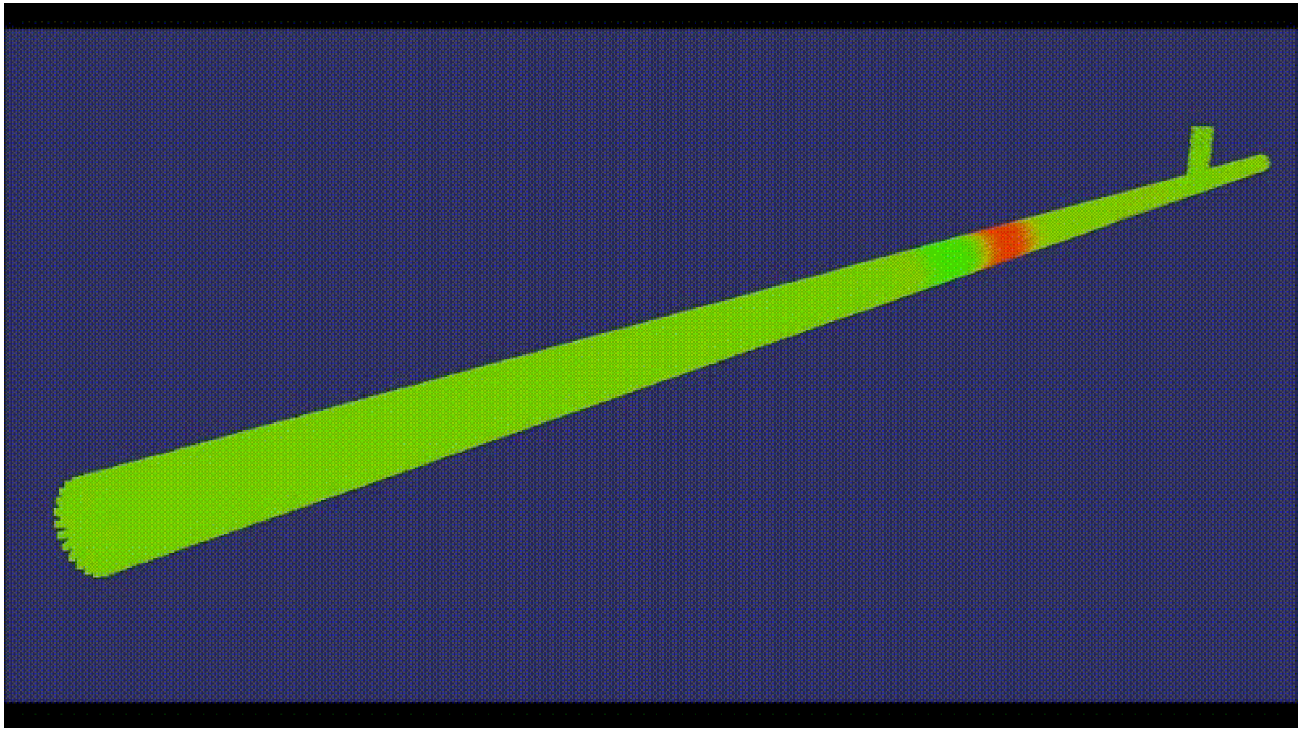




H Khawaja. Study of Sound Waves in Fluidized Bed using CFD-DEM Simulations. Particuology, 2017, 38: pp.126 - 133.
https://doi.org/j.partic.2017.07.002

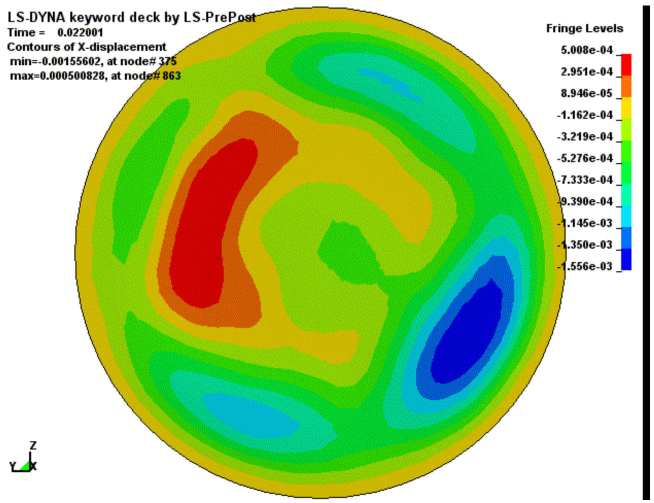
SHOCK-TUBE (VIDEO)

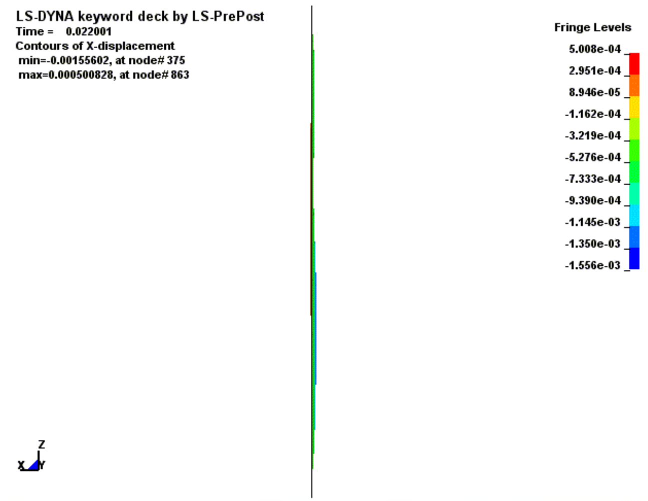
H Khawaja et al. Experimental and Numerical Study of Pressure in a Shock Tube. J Press Vess-T ASME, 2016, 138(4): 041301.
http://dx.doi.org/10.1115/1.4031591

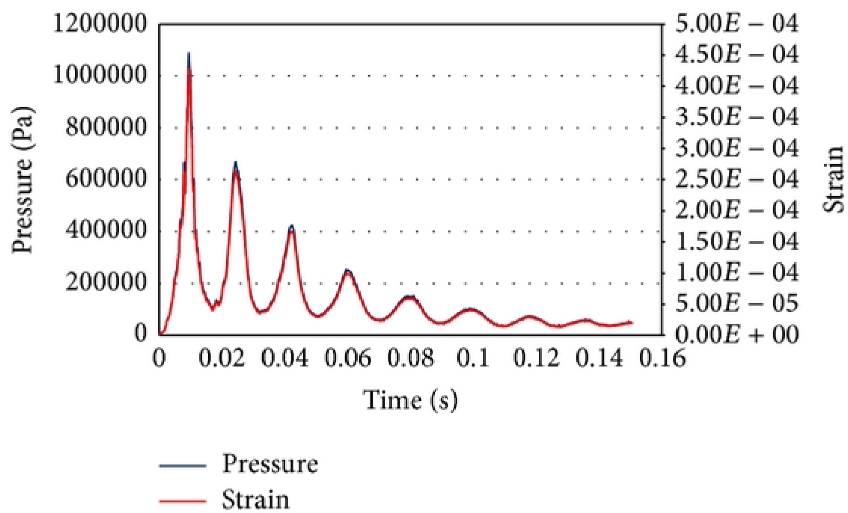


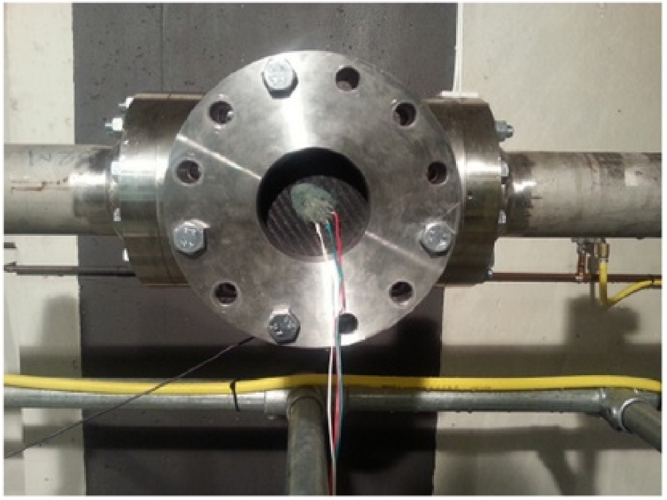
H Khawaja et al. Experimental and Numerical Study of Pressure in a Shock Tube. J Press Vess-T ASME, 2016, 138(4): 041301.
http://dx.doi.org/10.1115/1.4031591

CFRP DYNAMIC RESPONSE





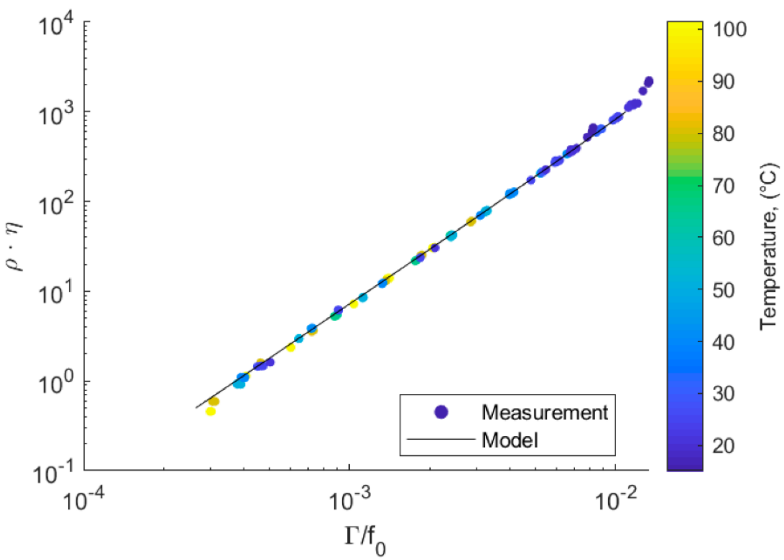


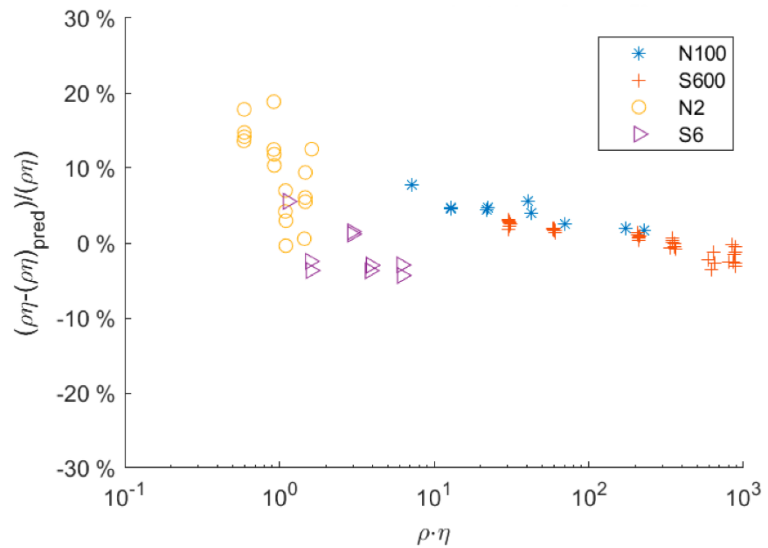


H Khawaja et al. Study of CRFP Shell Structures under Dynamic Loading in Shock Tube Setup. Journal of Structures, 2014. http://dx.doi.org/10.1155/2014/487809

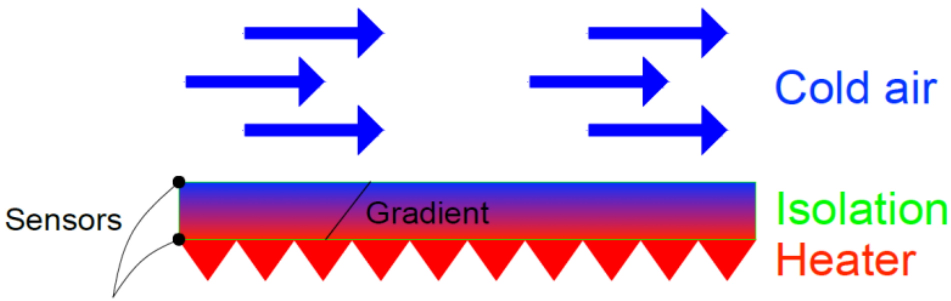
FLUID VISCOSITY-DENSITY SENSOR

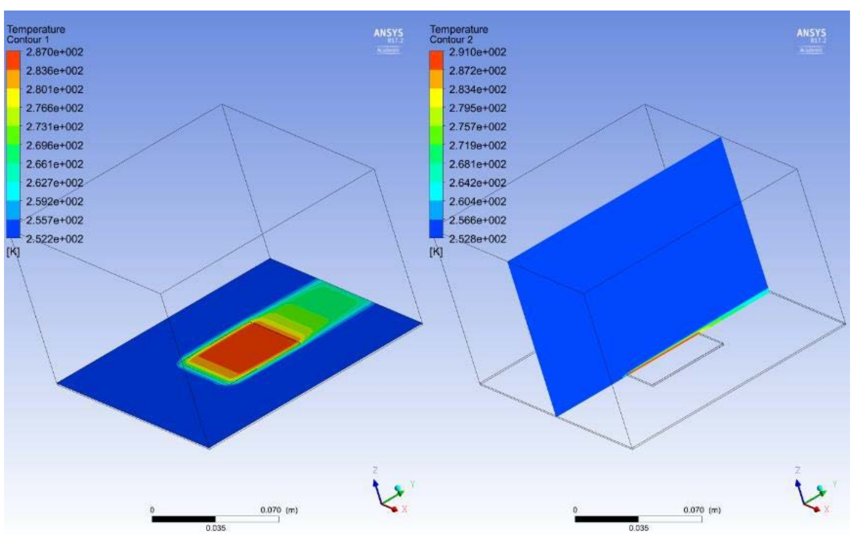
rheonics





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





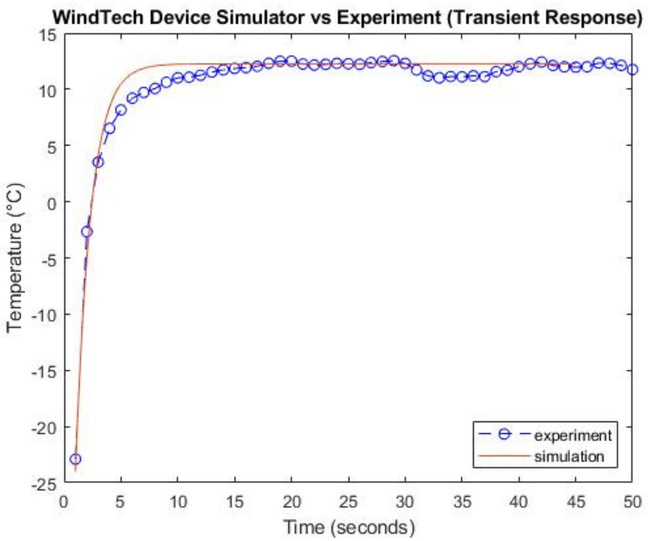
WindTech
WE DEVELOP COLD CLIMATE TECHNOLOGY

H Khawaja, D Swart, S Antonsen @ Windtech AS. Measuring Environmental Exposure. UK Patent GB 2588580. Link

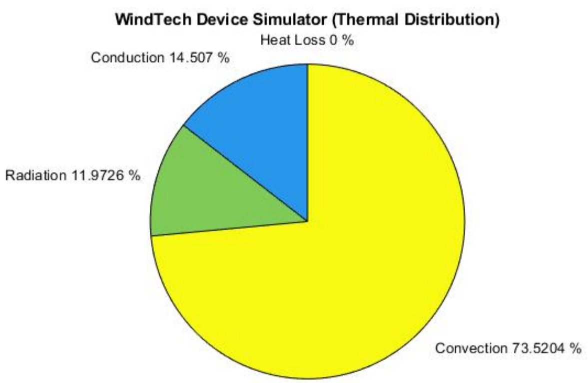
ENVIRONMENT EXPOSURE SENSOR

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

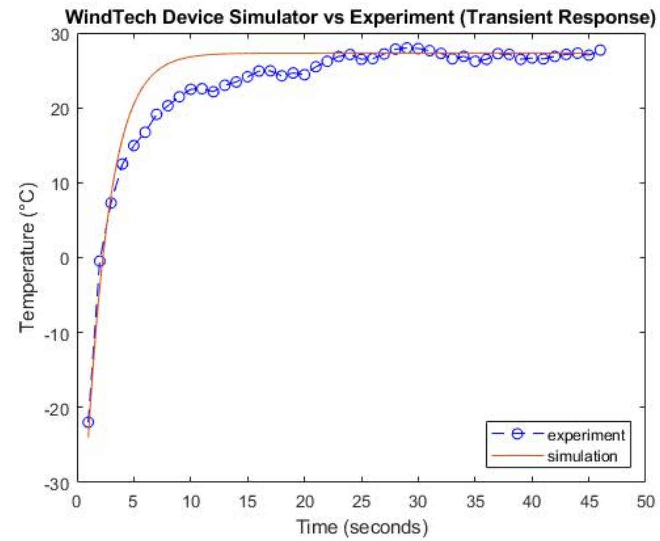
Wind Velocity = 8 m/s



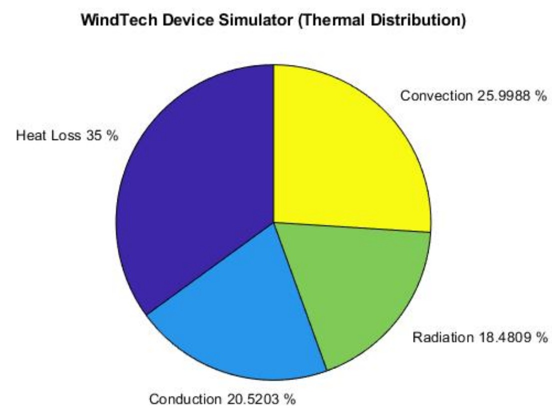
Heated Temperature = 12.1°C



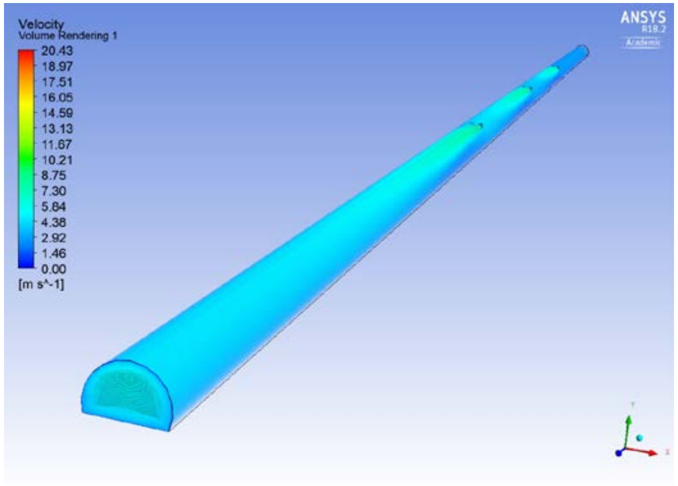
Wind Velocity = 0.5 m/s

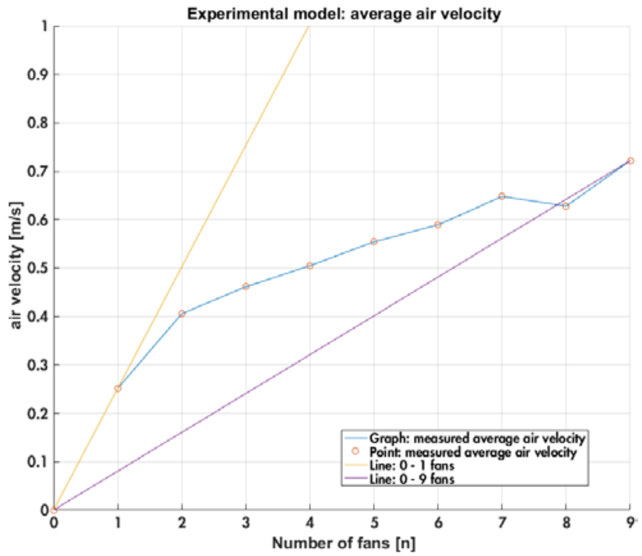


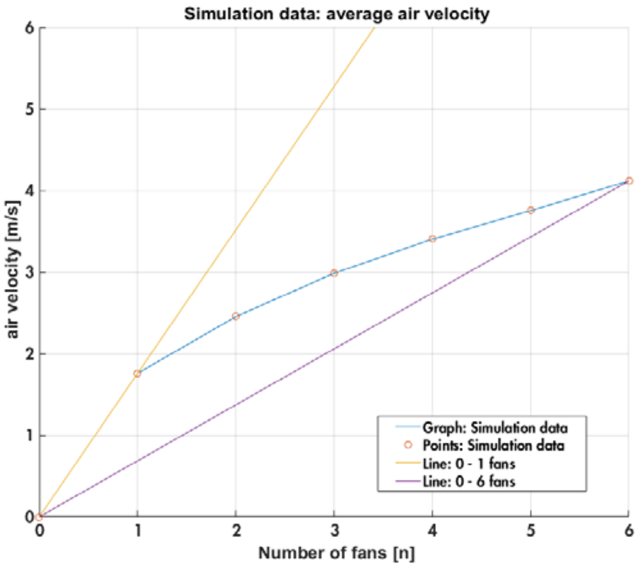
Heated Temperature = 26.9°C



H Khawaja, D Swart, S Antonsen @ Windtech AS. Measuring Environmental Exposure. UK Patent GB 2588580. Link

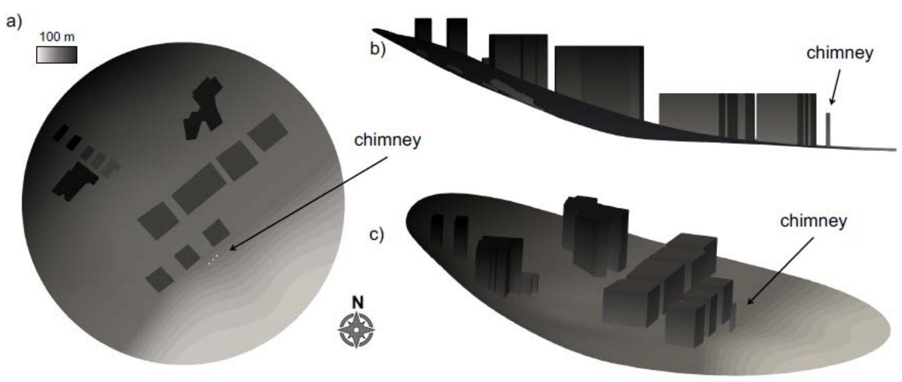


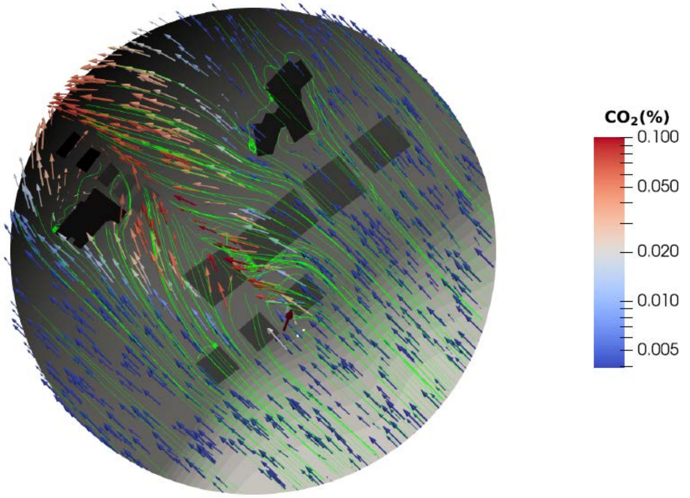


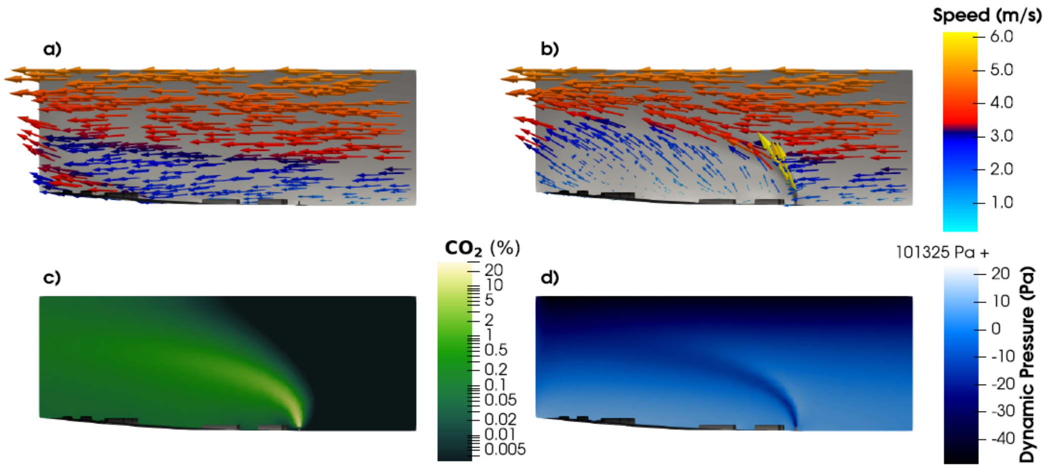


Torgeir Myrvang, Hassan Khawaja, Validation of air ventilation in tunnels, using experiments and computational fluid dynamics. The International Journal of Multiphysics, 2018, 12(3): pp. 295 - 311. http://dx.doi.org/10.21152/1750-9548.12.3.295

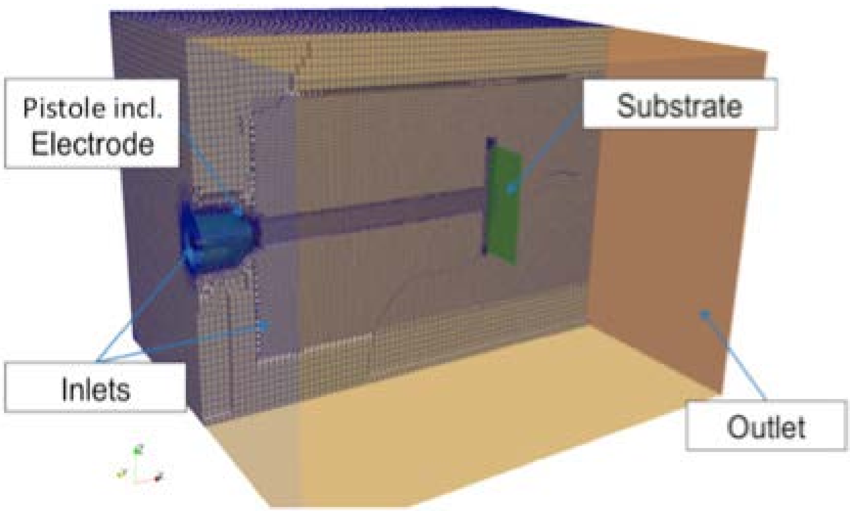
Exhaust Emissions – Tromsø Harbour

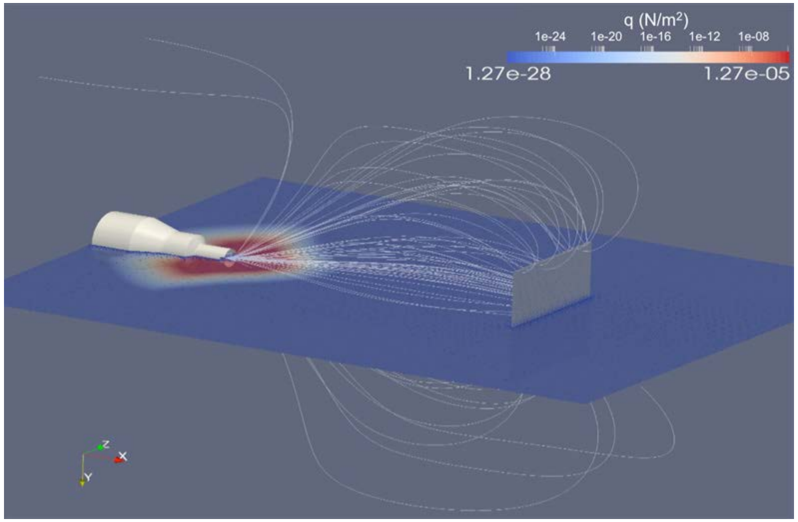


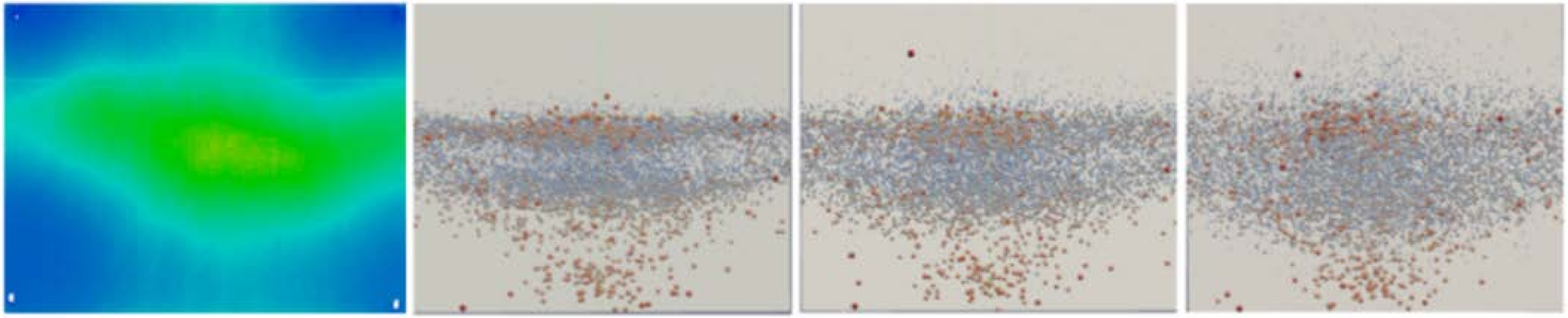




Asier Zubiga, Synne Madsen, Hassan Khawaja, Gernot Boiger. Atmospheric Contamination of Coastal Cities by the Exhaust Emissions of Docked Marine Vessels: the case of Tromsø. Environments, 2021, 8(9), 88. https://doi.org/10.3390/environments8090088



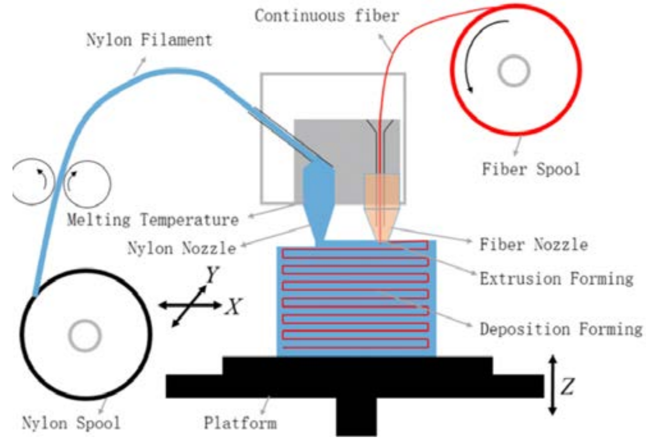


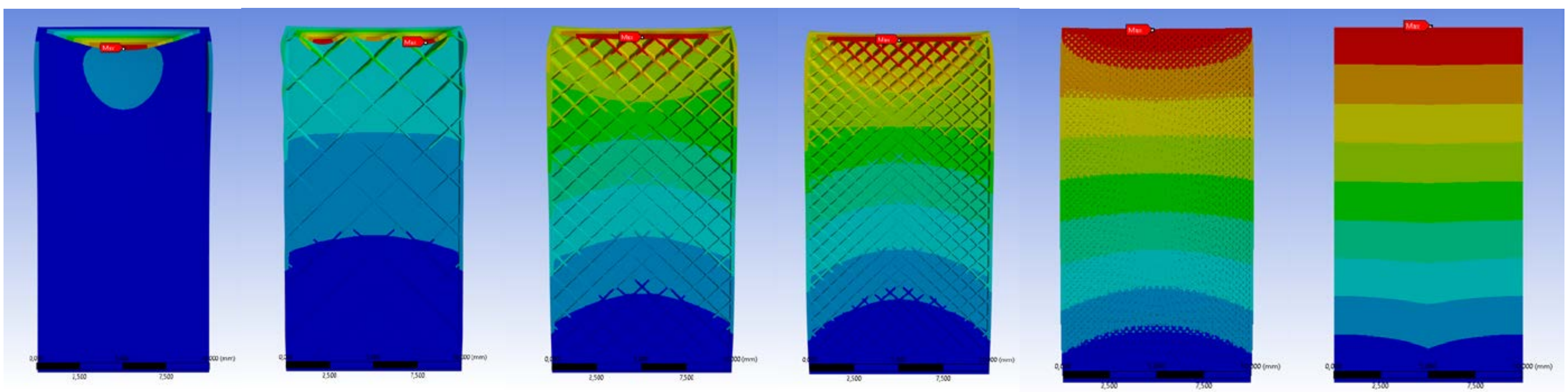


Experiment k-factor: 0.5 k-factor: 1 k-factor: 2

Gernot Boiger, Marlon Boldrini, Viktor Lienhard, Bercan Siyahhan, Hassan Khawaja, Mojtaba Moatamedi. Multiphysics Eulerian-Lagrangian Electrostatic Particle Spray Model for OpenFOAM® and KaleidoSim® Cloud-Platform. The International Journal of Multiphysics, 2020, 14(1): pp.1-16. http://dx.doi.org/10.21152/1750-9548.14.1.1

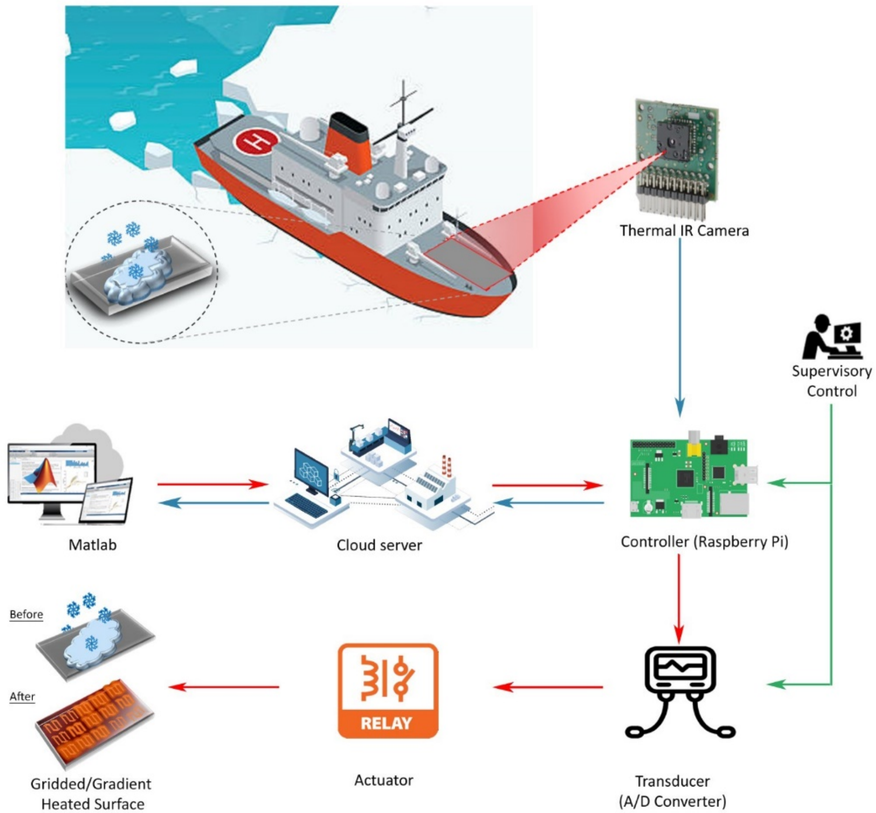
Mechanical Properties of 3D Printed Materials





Zahra Andleeb, Hassan Khawaja, Kristian Andersen and Mojtaba Moatamedi. Finite Element Analysis to determine the impact of Infill density on Mechanical Properties of 3D Printed Materials. The International Journal of Multiphysics, 2022, 16(3), pp. 317-335. https://doi.org/10.21152/1750-9548.16.3.317

USING IR FOR ICE DETECTION AND MITIGATION (nICE)



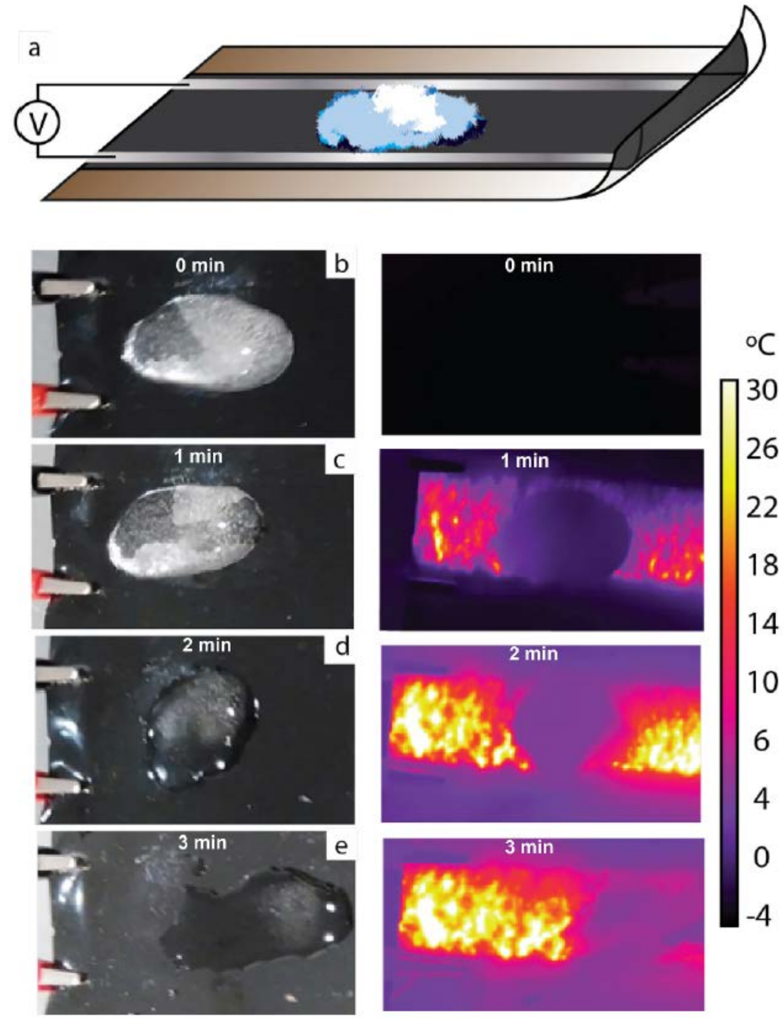


Fig. 4. De-icing demonstration of R2R CNT coated sheet (IR and colour images), when ice is frozen inside cold room at steady state temperature of −2 °C.

Taimur Rashid, Hsin-Ling Lang, Madiha Taimur, Nicolò Chiodarelli, Michael De Volder, Kåre Edvardsen, Hassan Khawaja. Roll to Roll coating of carbon nanotube films for electro thermal heating. Cold Regions Science and Technology, 2021, 182: 103210. https://doi.org/10.1016/j.coldregions.2020.103210

Microstructure Characterstics for Optimizing Material Parameters

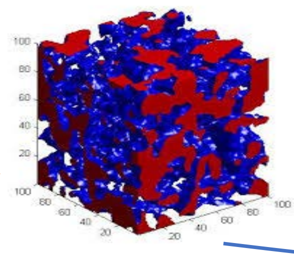
Digital Twin Model
- Sphere Packing
- Gaussian Random Fields
- Etc.

Material Parameters
- Sintering temperature
- Phase types
- Volume fractions
- Etc.

Tomography

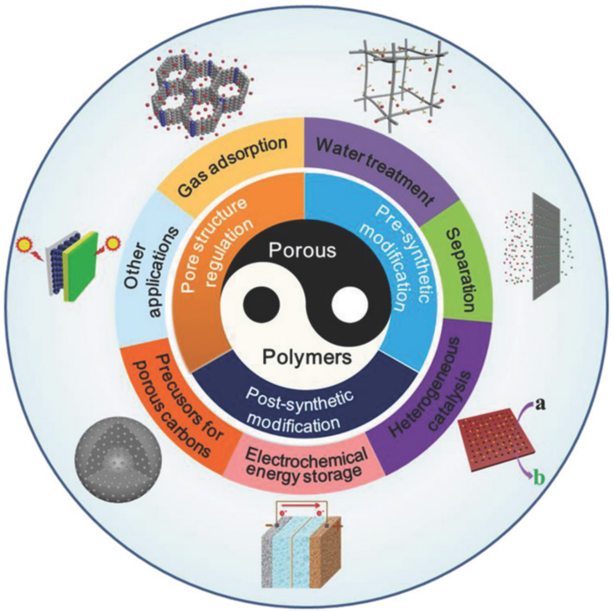
2D-Images

3D microstructure of real or synthetic data

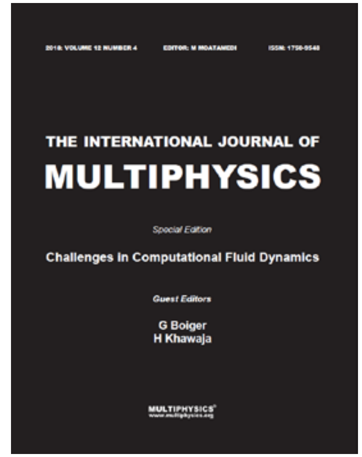


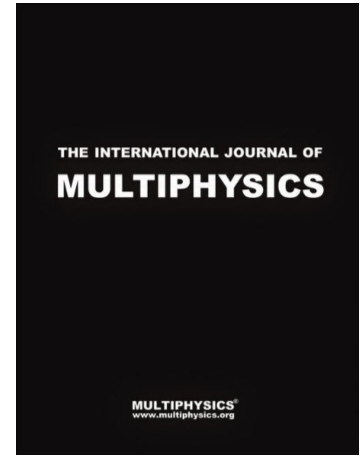
Characteristics
- Porosity
- Tortuosity
- Conductivity
- Etc.

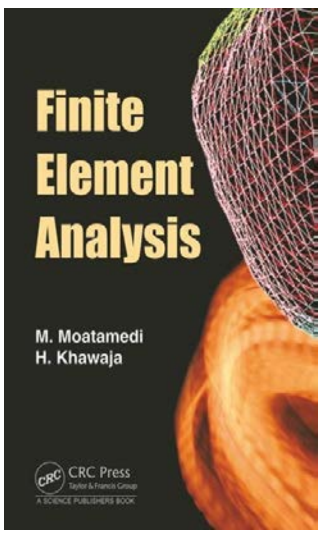
Effective Properties
- Permeability
- Conductivity
- Capacity
- Etc.

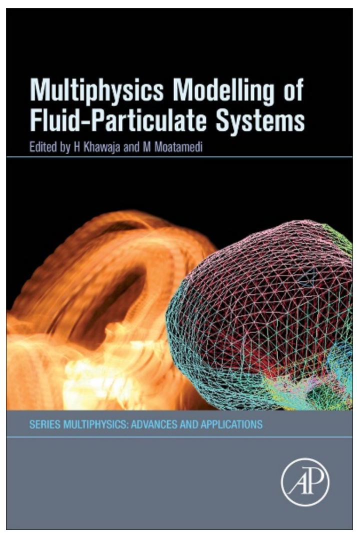


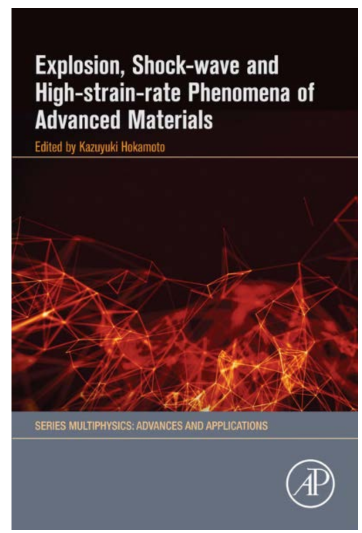
INTERNATIONAL SOCIETY OF MULTIPHYSICS

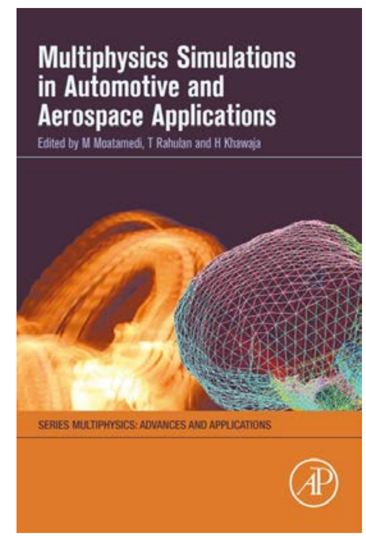












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QUESTIONS/COMMENTS

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https://www.linkedin.com/in/hassan-khawaja