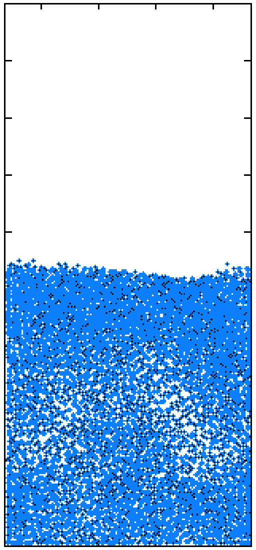
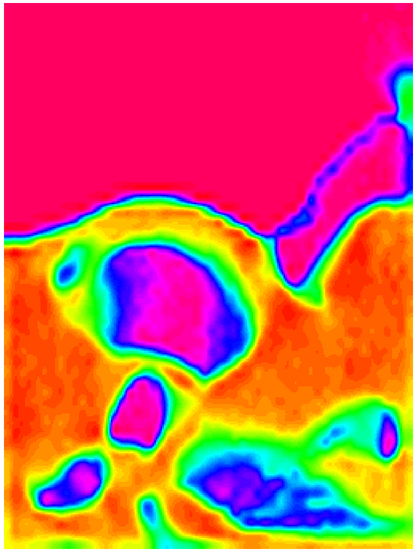
Computational Fluid Dynamics - A Steppingstone of Multiphysics





Hassan Abbas Khawaja

BEng (Aero) MPhil PhD (Cantab) MIET PE CEng

PRESENTATION OVERVIEW

- INTRODUCTION
  - Presenter's Bio

- COMPUTATIONAL FLUID DYNAMICS
  - Historical Evolution of Computational Fluid Dynamics
  - What is MULTIPHYSICS simulation?

- EXAMPLES
  - Micro-Fluidic Valve
  - Fluidized Bed
  - Shock-Tube
  - Drop Test
  - Tensile Test
  - Viscosity-Density Sensor
  - Femur Bone
  - Cold Room
  - Thermal Diffusion
  - Fish Cage
  - Contact Profile
  - Conjugate Heat Transfer

- SOCIETY & TRIBUTE

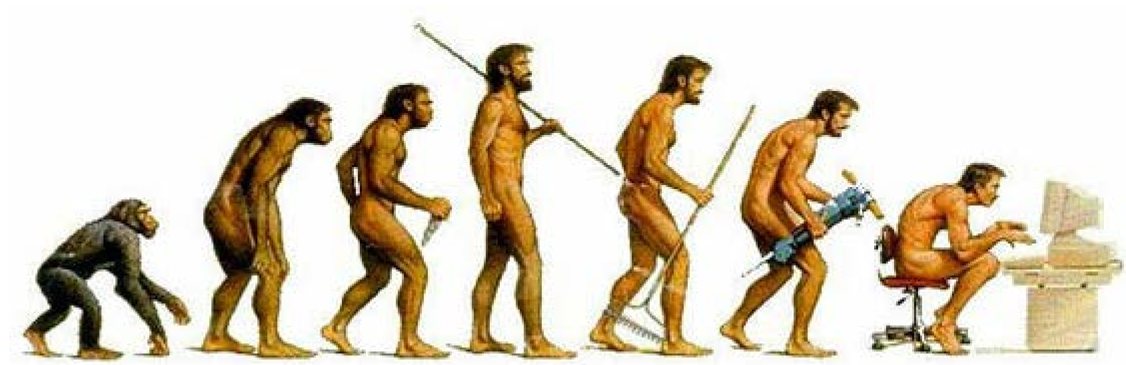
PRESENTER'S BIO

PRESENTER'S BIO

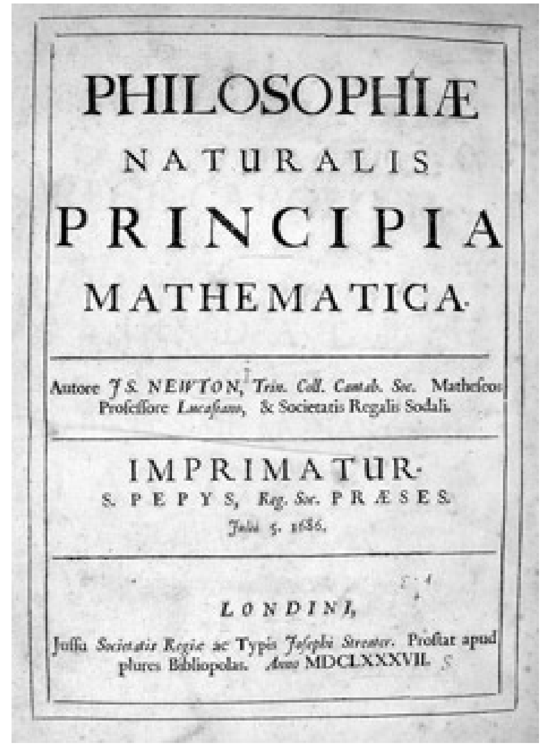
IR, Spectroscopy, and Numerical Modelling Research Group.
https://en.uit.no/forskning/forskningsgrupper/gruppe?p_document_id=418239

UiT / THE ARCTIC UNIVERSITY OF NORWAY

EVOLUTION OF FLUID MECHANICS



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



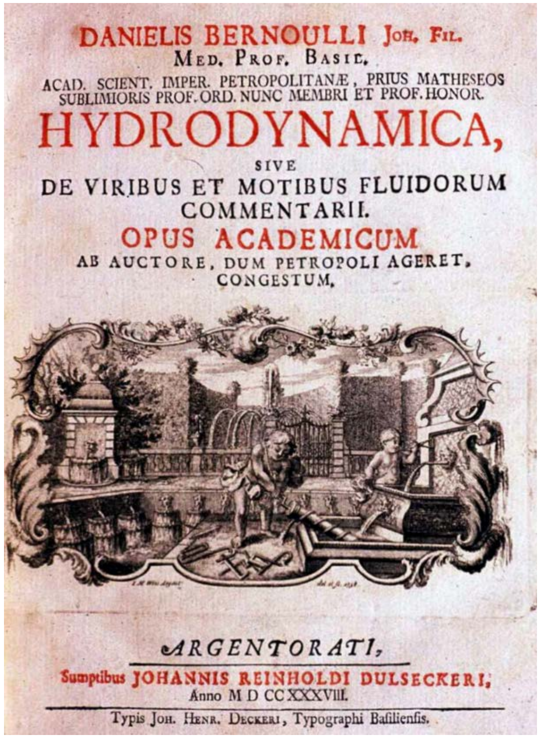
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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.

$$F = ma$$



DANIELIS BERNOULLI JOH. FIL.
MED. PROF. BASIL.
ACAD. SCIENT. IMPER. PETROPOLITANÆ, PRIUS MATHESEOS SUBLIMIORIS PROF. ORD. NUNC MEMBRI ET PROF. HONOR.

HYDRODYNAMICA,

SIVE
DE VIRIBUS ET MOTIBUS FLUIDORUM COMMENTARII.

OPUS ACADEMICUM
AB AUCTORE, DUM PETROPOLI AGERET, CONGESTUM.

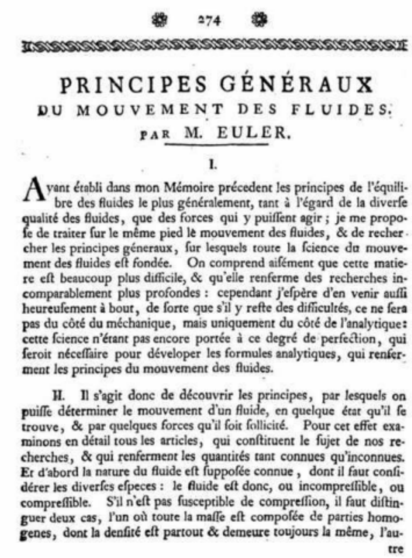
ARGENTORATI,
Sumptibus JOHANNIS REINHOLDI DULSECKERI,
Anno M D CCXXXVIII.
Typis JOH. HENR. DECKERI, Typographi Basiliensis.

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

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 le mouvement des fluides, & de rechercher les principes géneraux, 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.

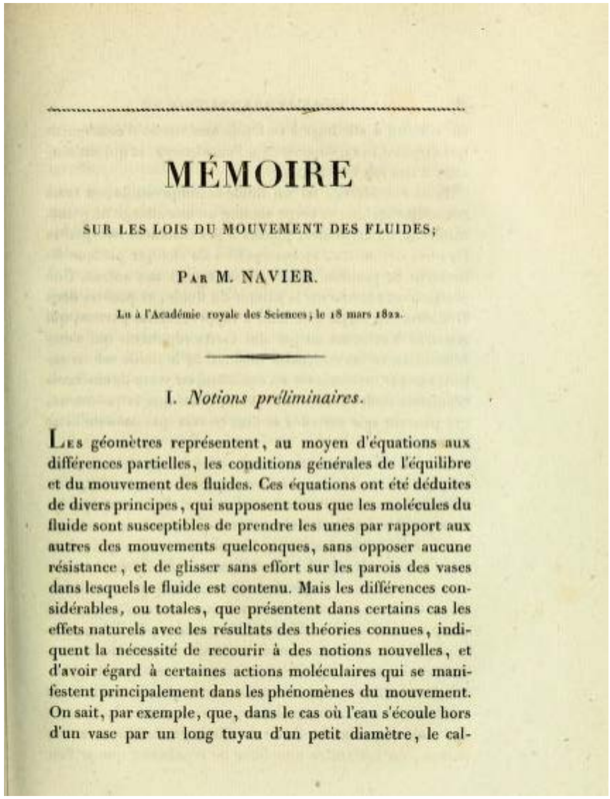
II. Il s'agit donc de découvrir les principes, par lesquels on puiſſe déterminer le mouvement d'un fluide, en quelque état qu'il ſe trouve, & par quelques forces qu'il ſoit ſollicité. Pour cet effet examinons en détail tous les articles, qui conſtituent le ſujet de nos recherches, & qui renferment les 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-

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

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

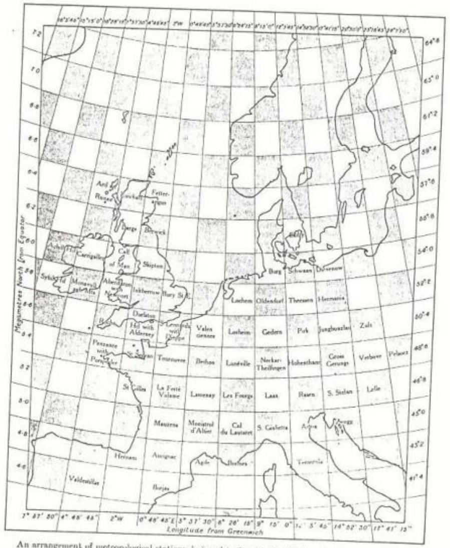
NOTABLE OTHERS

Augustin-Louis Cauchy (1789-1857)

Siméon Denis Poisson (1781-1840)

Jean Léonard Marie Poiseuille (1797-1869)

Joseph-Louis Lagrange (1736-1813)



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

$\Delta t = 12, 24h$

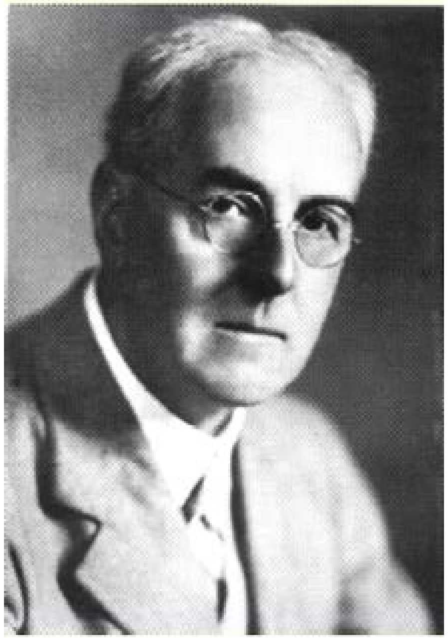
$\Delta p = 150 mb$!

numerically unstable !

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

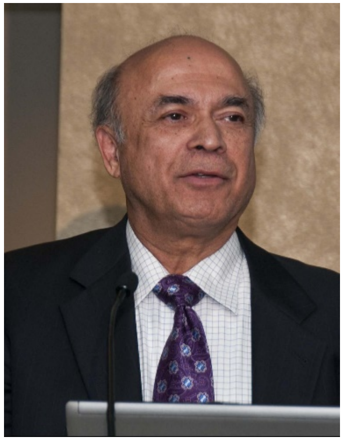
CAMBRIDGE
AT THE UNIVERSITY PRESS
1922

19



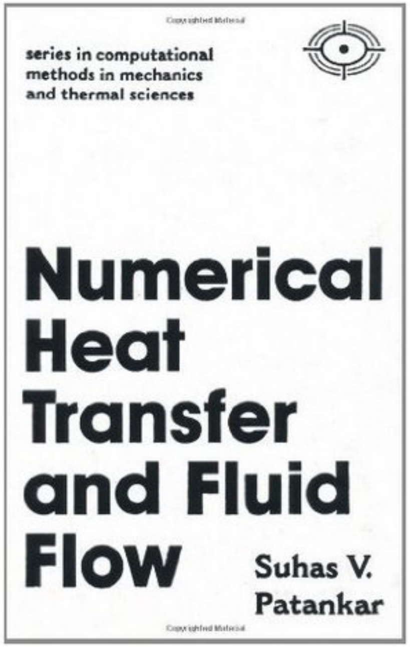
Lewis Fry Richardson (1881 – 1953)

SEMI-IMPLICIT PRESSURE LINKED EQUATION (1979)



Shuhas V. Patankar (1941-)

Dudley Brian Spalding (1923 – 2016)

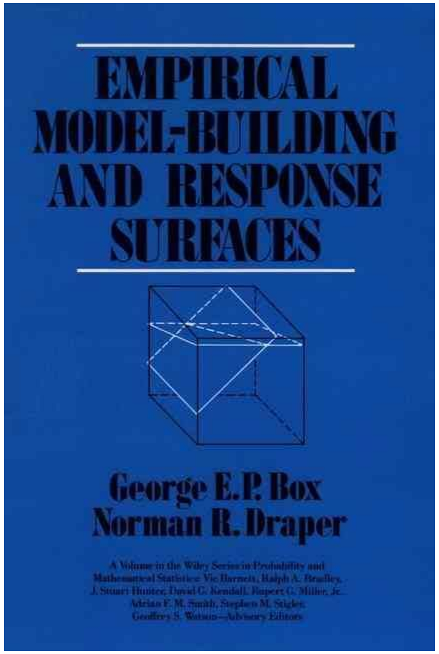


WORDS OF CAUTION (1987)

"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 Box (1987)



Box, George E. P.; Norman R. Draper (1987). Empirical Model-Building and Response Surfaces, p. 424, Wiley. ISBN 0471810339.

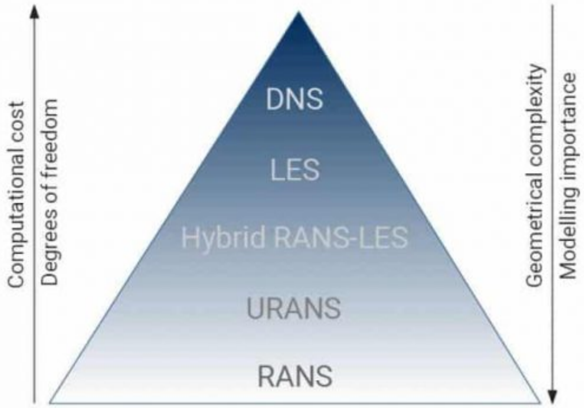
IBM PS/2 Machine (1987)
Source: https://www.computerhistory.org/

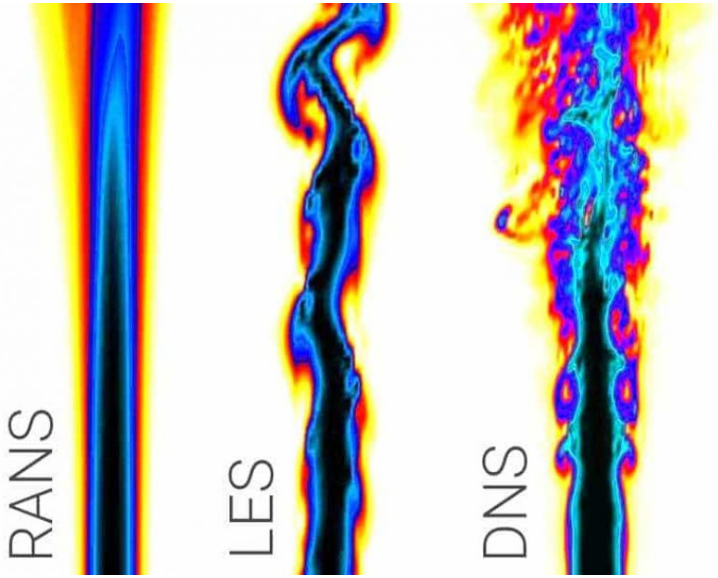
*"Colorful Fluid Dynamics", an old pun on the Computational Fluid Dynamics acronym, CFD, can be divisive. Doug McLean, Boeing Technical Fellow (retired), offered the following perspective from his exceptional book entitled Understanding Aerodynamics [1]: "***These days it is common to see a complicated 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***".*

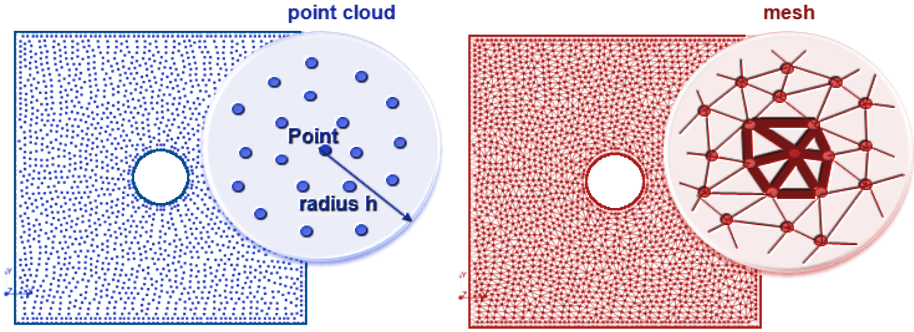
*Professor Phil Roe, Univ. of Michigan, makes a provocative comment in his recorded lecture entitled "Colorful Fluid Dynamics: Behind the Scenes" [2]. He states that "***Even inaccurate CFD can be useful***". He further notes that "***The power of detailed visualization makes CFD more rich in information than experiment***". Few would disagree that CFD simulation results innately contain a wealth of opportunity for insight and communication.*

[1] McLean, D., "Understanding Aerodynamics" (2013), p.492, John Wiley & Sons, Ltd.
[2] Roe, P., "Colorful Fluid Dynamics: Behind the Scenes", retrieved from https://bit.ly/2IqE4gX

CFD TODAY (2021)

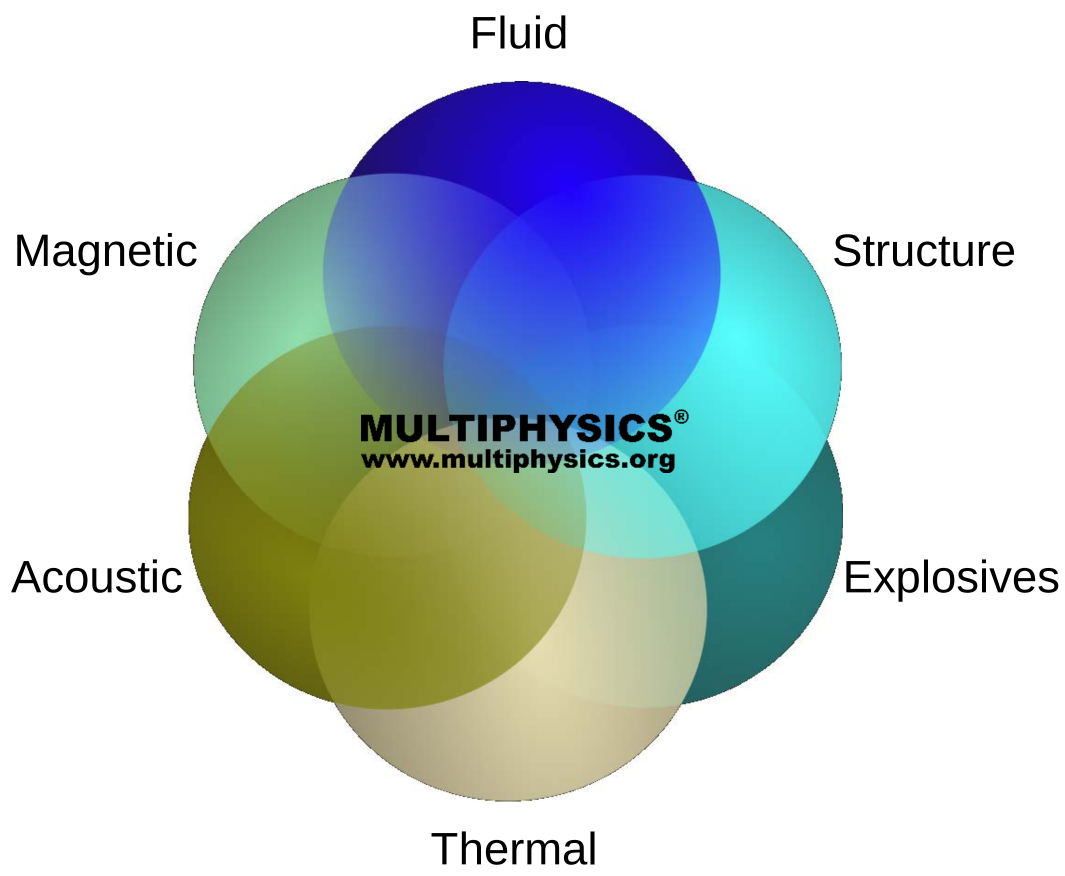




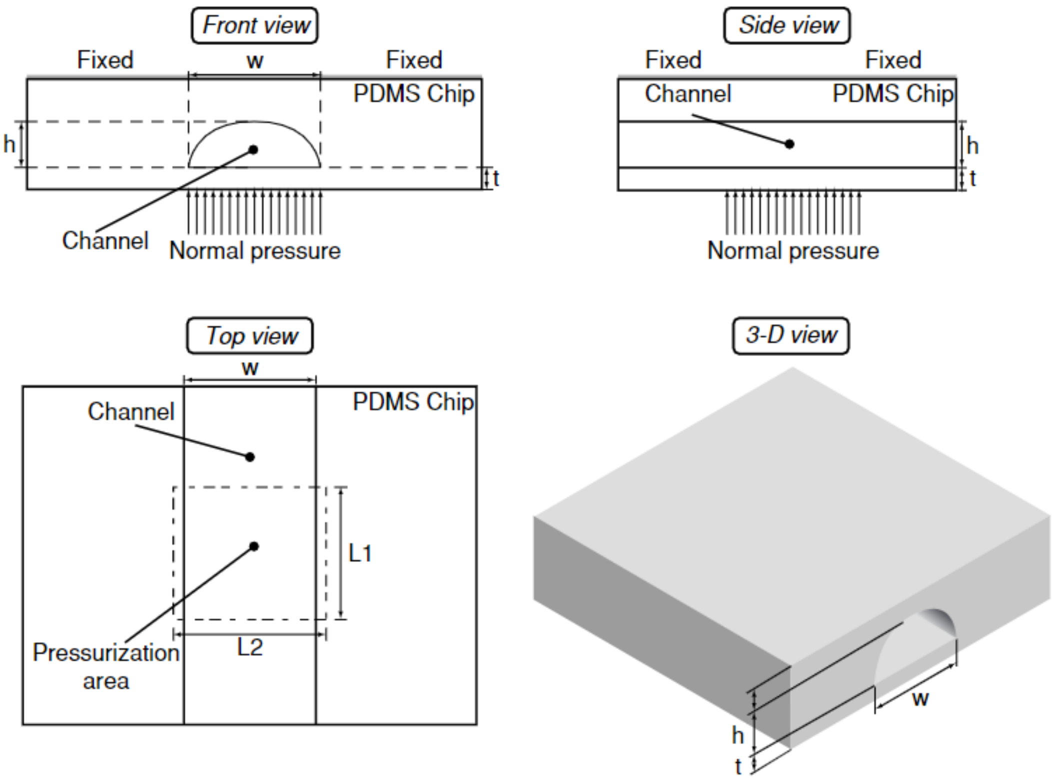


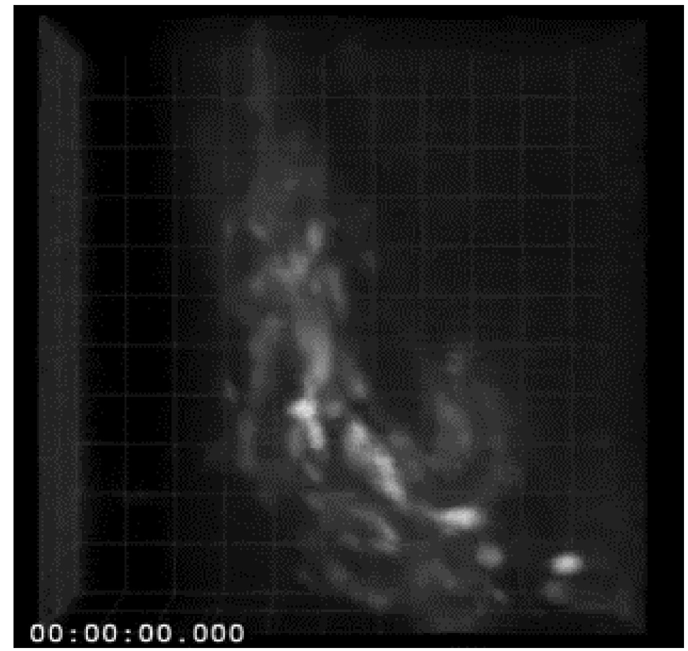
WHAT'S NEXT?

WHAT IS MULTIPHYSICS SIMULATION?

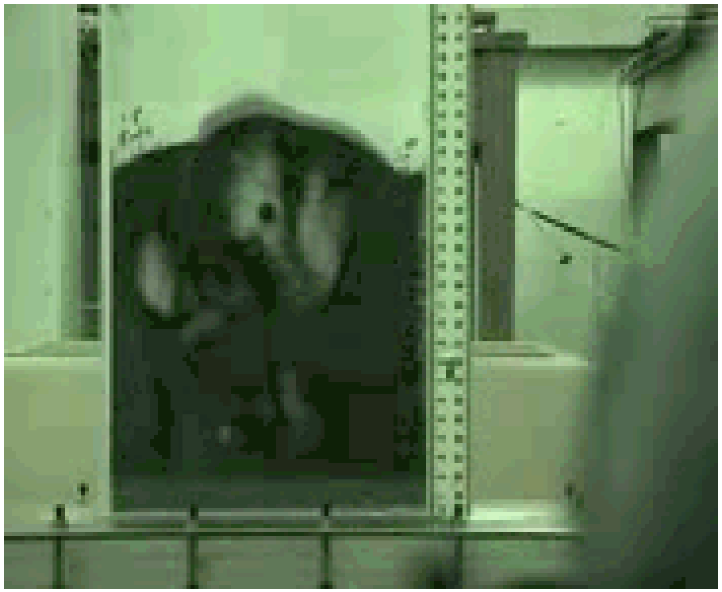


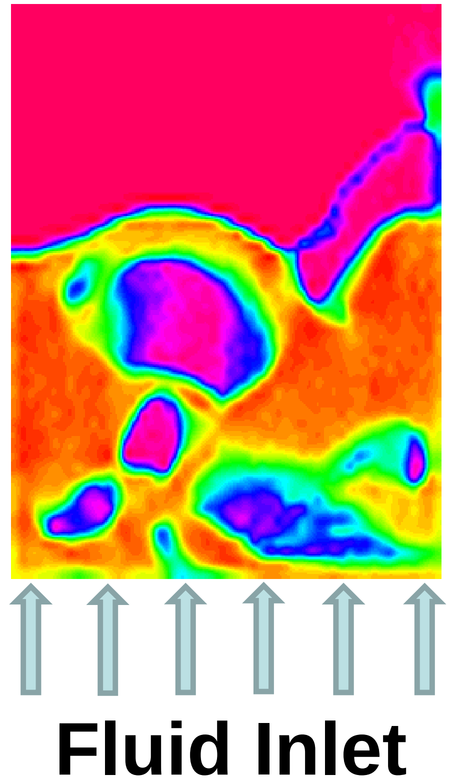
MICRO-FLUIDIC VALVE

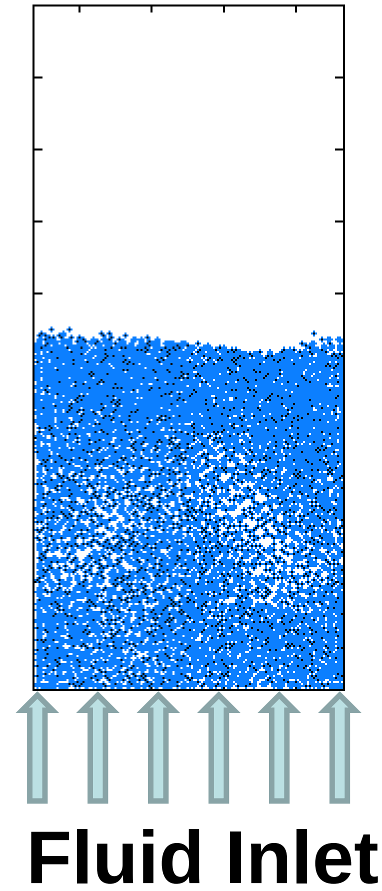




H Khawaja, I Raouf, K Parvez, A Scherer. Optimization of elastomeric micro-fluidic valve dimensions using nonlinear finite element methods. The International Journal of Multiphysics, 2009, 3(2): pp. 187 - 200. http://dx.doi.org/10.1260/175095409788837847

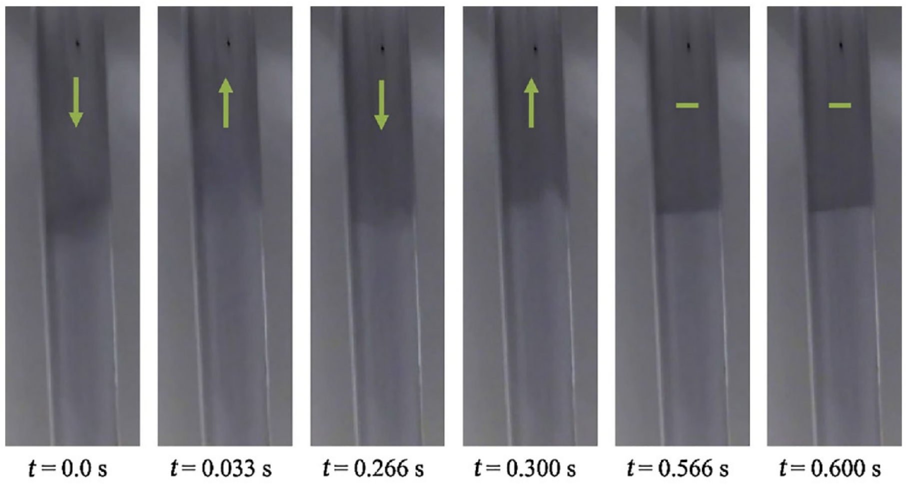


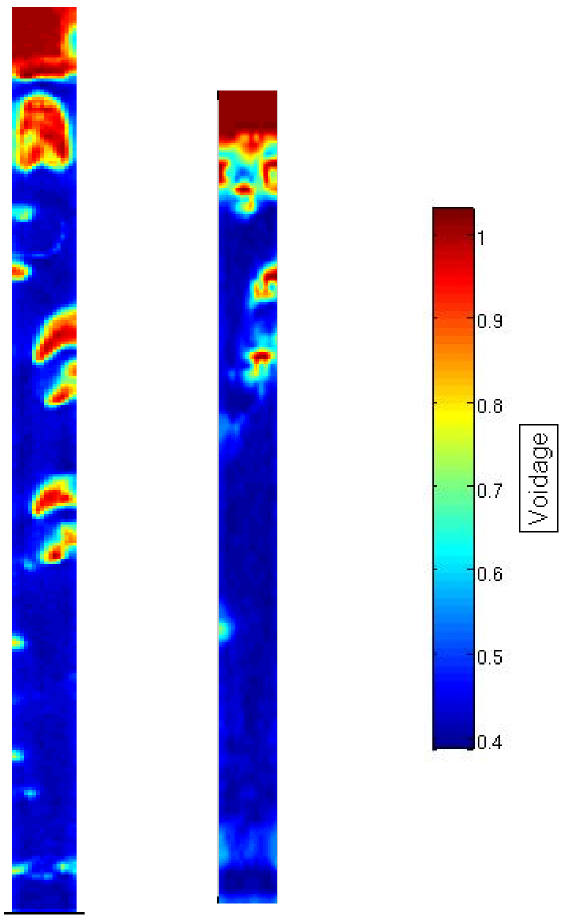




H Khawaja, M Moatamedi. Multiphysics Modelling of Fluid-Particulate Systems. Academic Press, 2020, ISBN 978-0-1281-8345-8.
https://doi.org/10.1016/C2018-0-02737-1

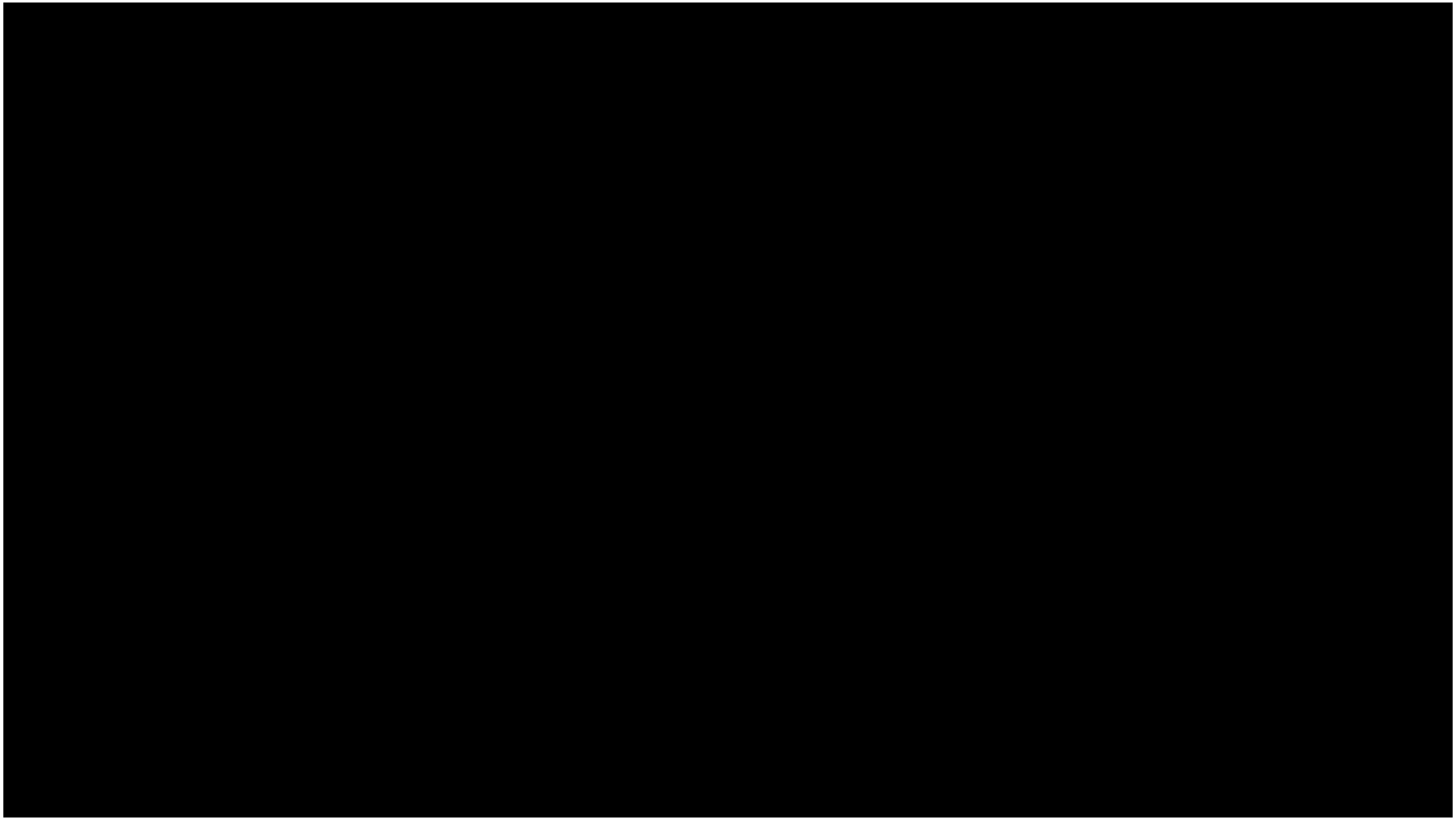
FLUIDIZED BED – SOUND WAVES





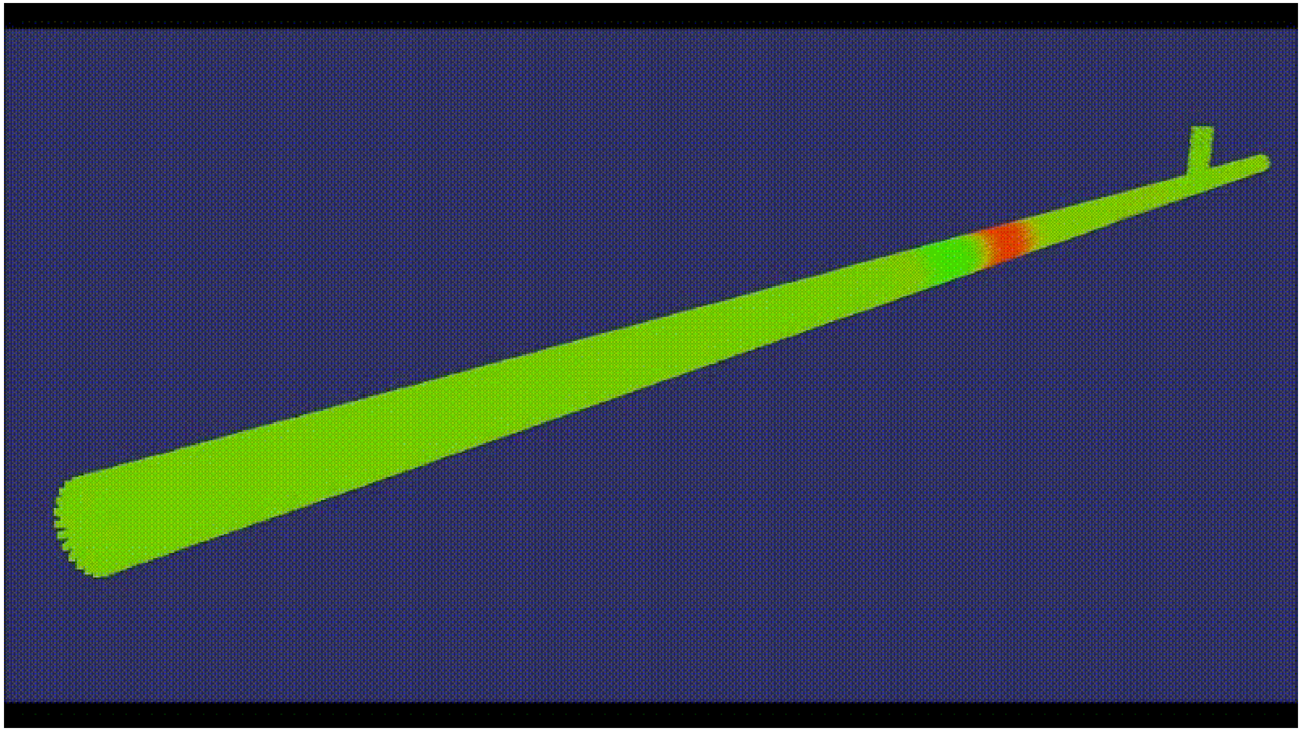
H Khawaja. Study of Sound Waves in Fluidized Bed using CFD-DEM Simulations. Particuology, 2017, 38: pp.126 - 133.
https://doi.org/j.partic.2017.07.002

SHOCK-TUBE (VIDEO)



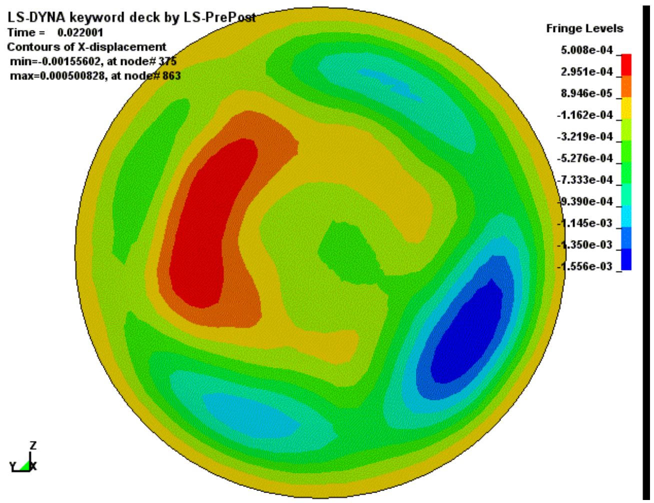
H Khawaja et al. Experimental and Numerical Study of Pressure in a Shock Tube. J Press Vess-T ASME, 2016, 138(4): 041301.
http://dx.doi.org/10.1115/1.4031591

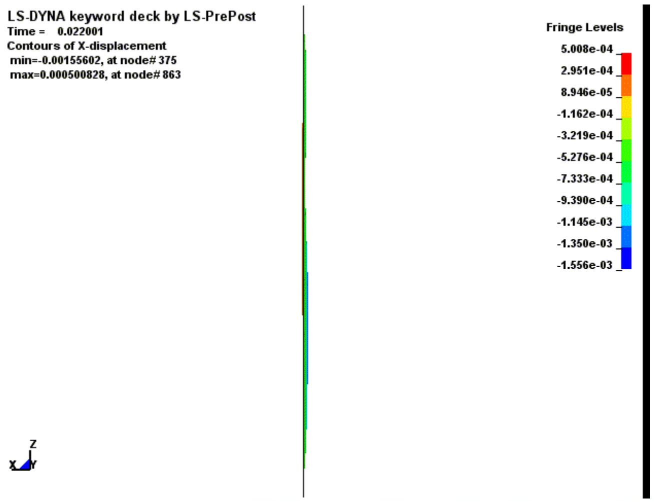
SHOCK-TUBE

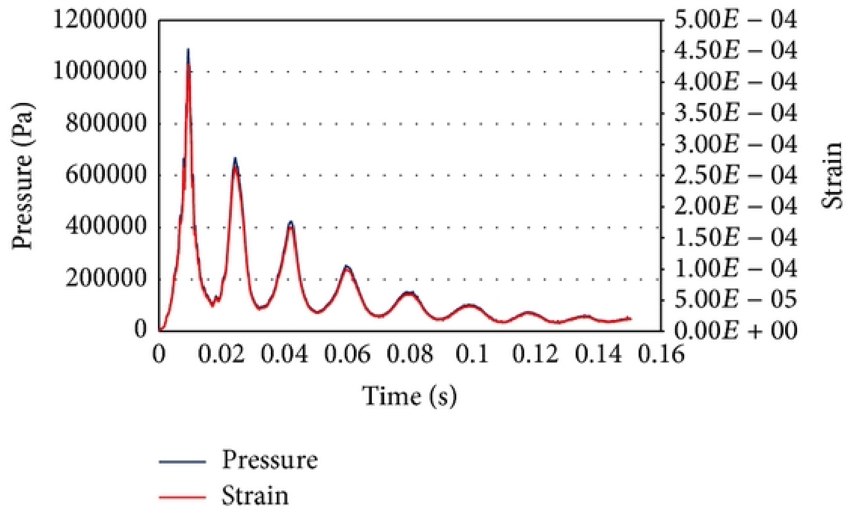


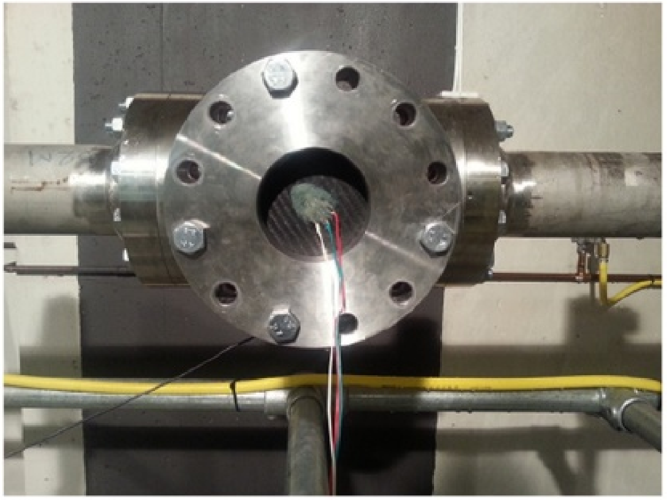
H Khawaja et al. Experimental and Numerical Study of Pressure in a Shock Tube. J Press Vess-T ASME, 2016, 138(4): 041301.
http://dx.doi.org/10.1115/1.4031591

CFRP Dynamic Response



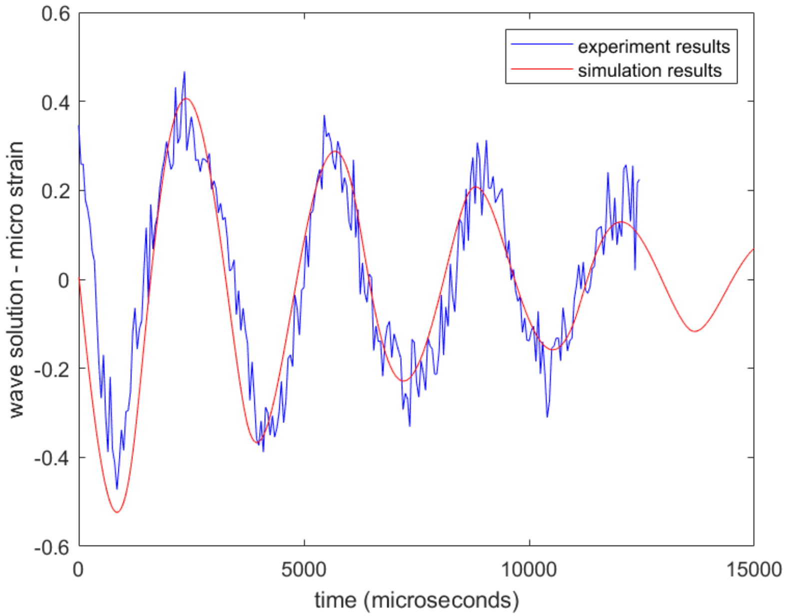






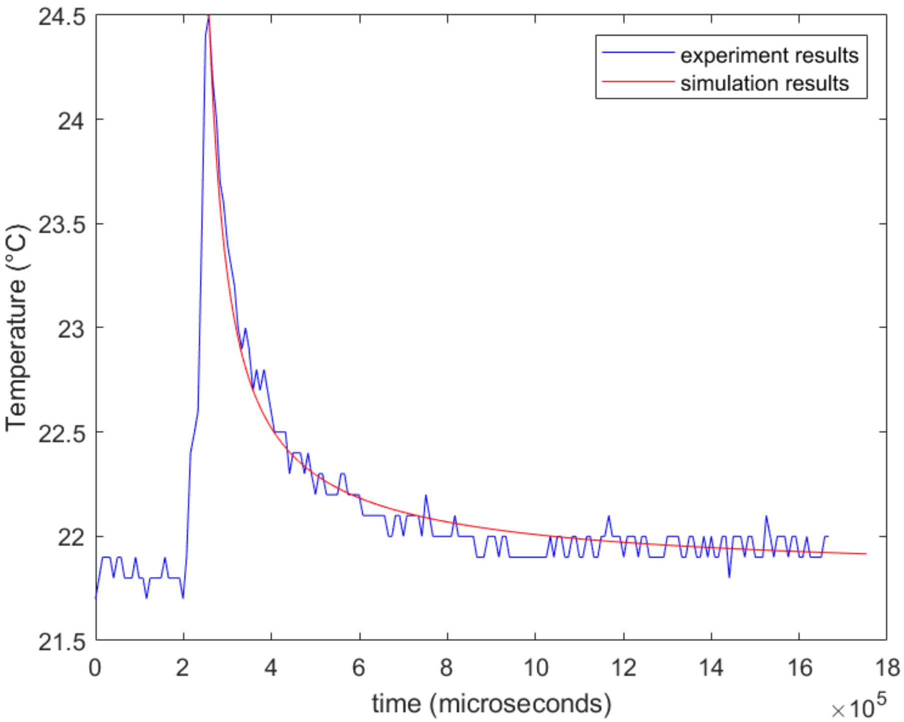
H Khawaja, T Bertelsen, R Andreassen, M Moatamedi. Study of CRFP Shell Structures under Dynamic Loading in Shock Tube Setup. Journal of Structures, 2014. http://dx.doi.org/10.1155/2014/487809

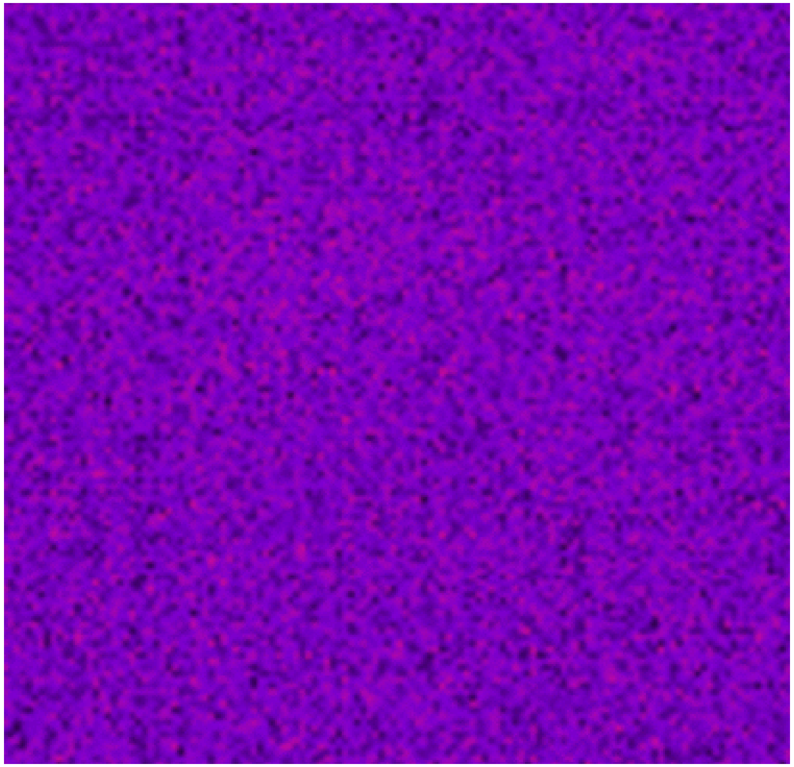
CFRP Drop Test



Z Andleeb, S Malik, H Khawaja, A Nordli, S Antonsen, G Hussain, M Moatamedi. Thermoelastic Investigation of Carbon-Fiber-Reinforced Composites using Drop Weight Impact Test. Applied Sciences, 2021, 11(1): 207. https://doi.org/10.3390/app11010207

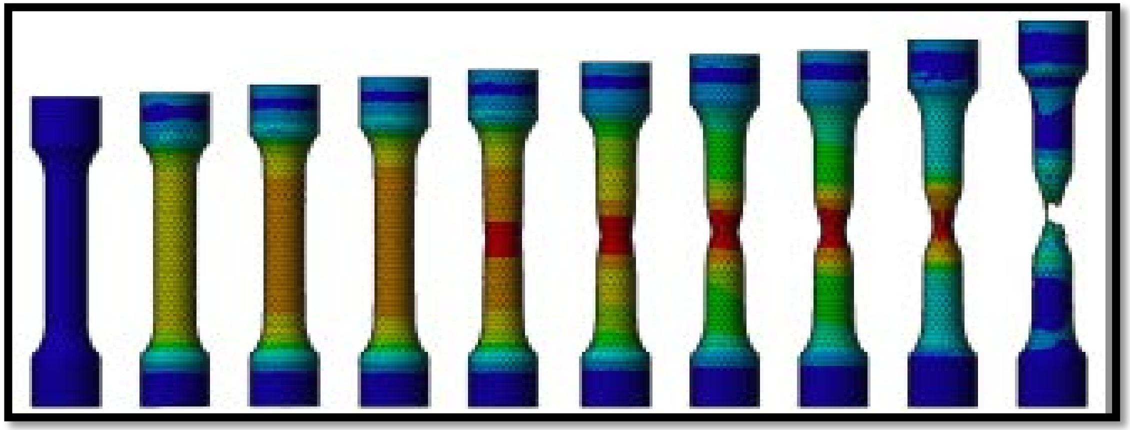
CFRP DROP TEST

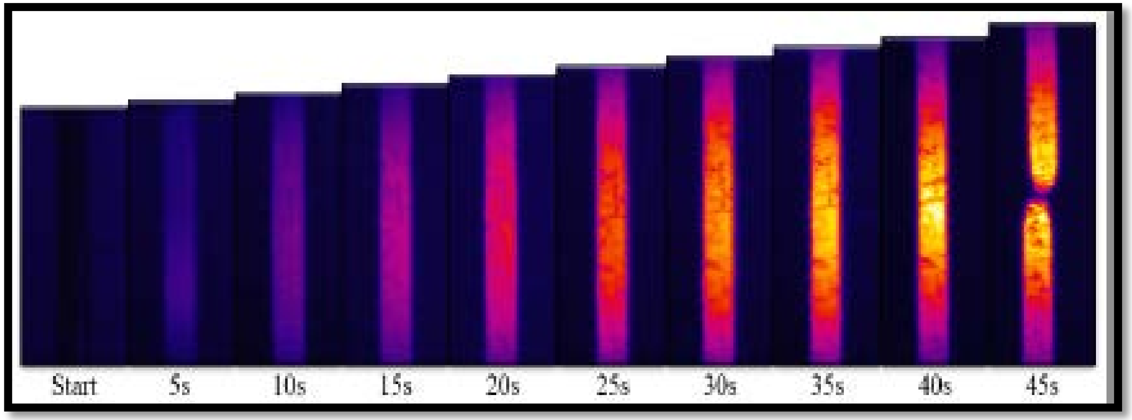




Z Andleeb, S Malik, H Khawaja, A Nordli, S Antonsen, G Hussain, M Moatamedi. Thermoelastic Investigation of Carbon-Fiber-Reinforced Composites using Drop Weight Impact Test. Applied Sciences, 2021, 11(1): 207. https://doi.org/10.3390/app11010207

TENSILE TEST





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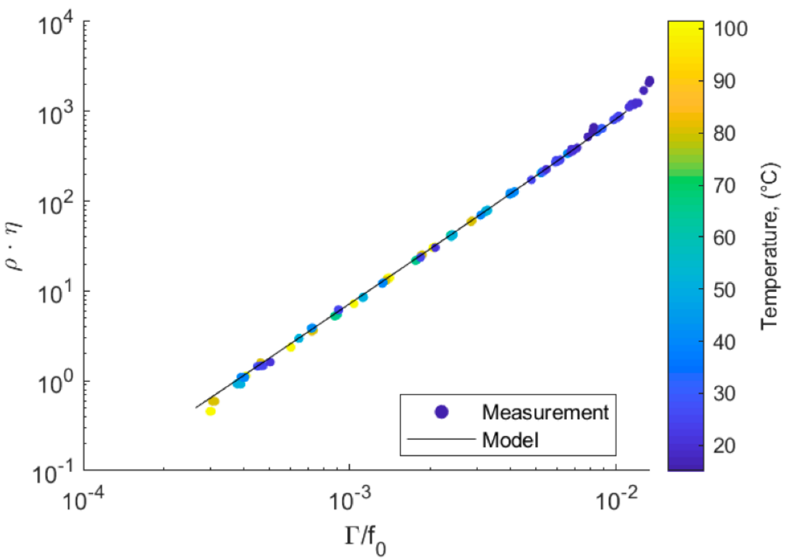

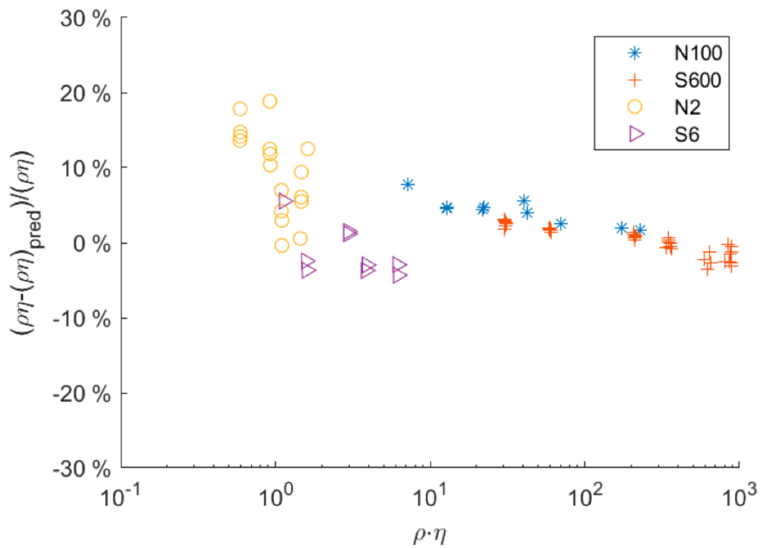

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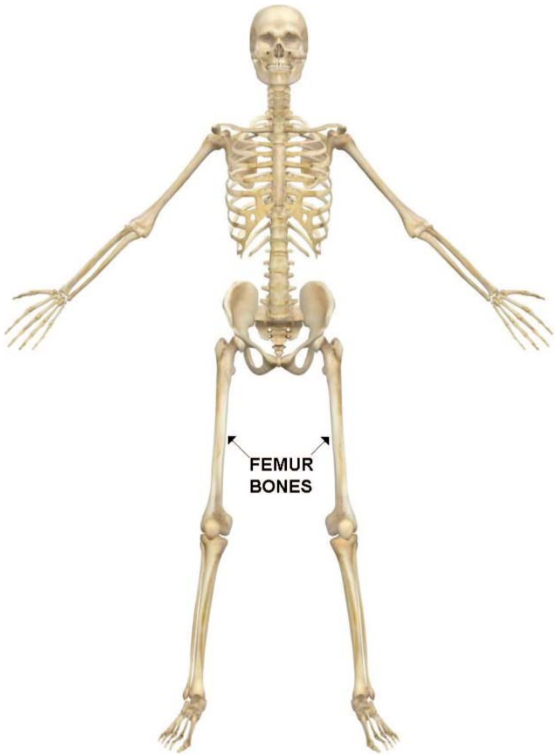

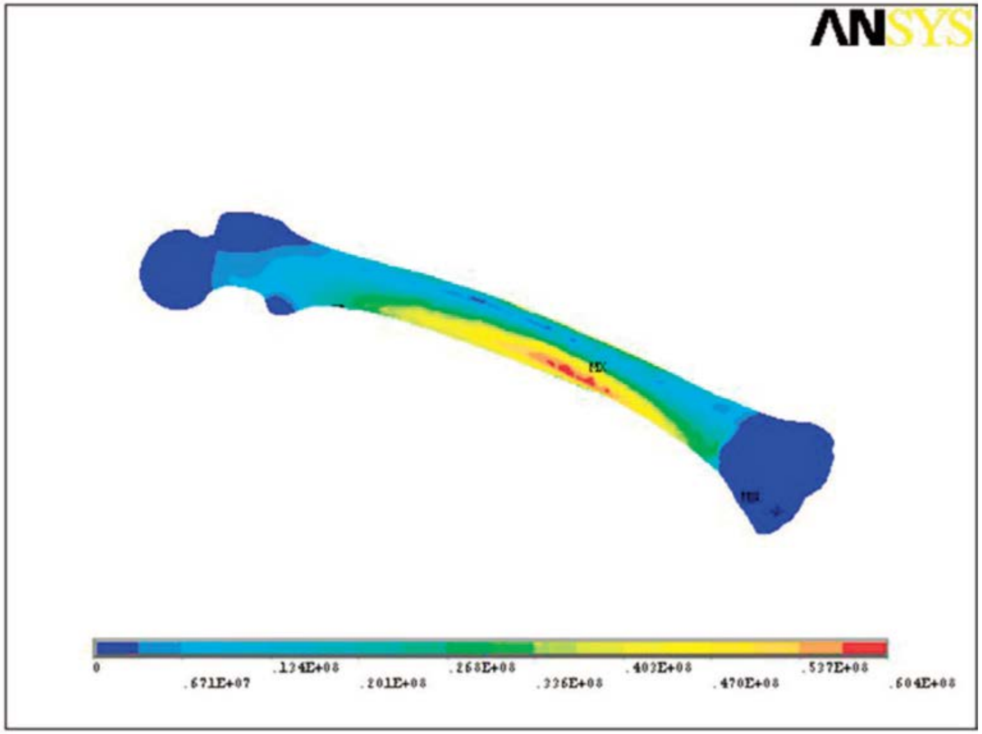

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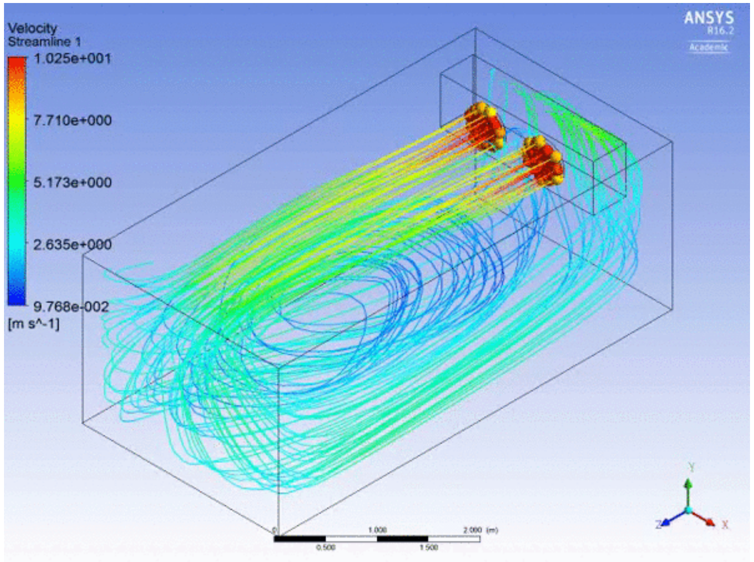

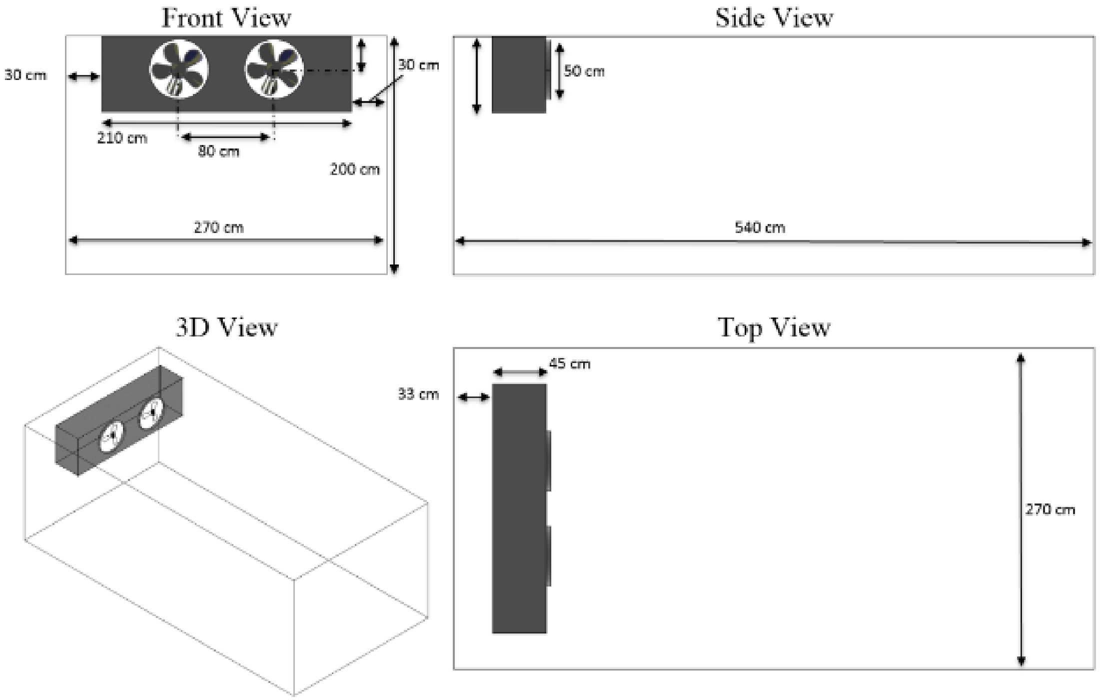

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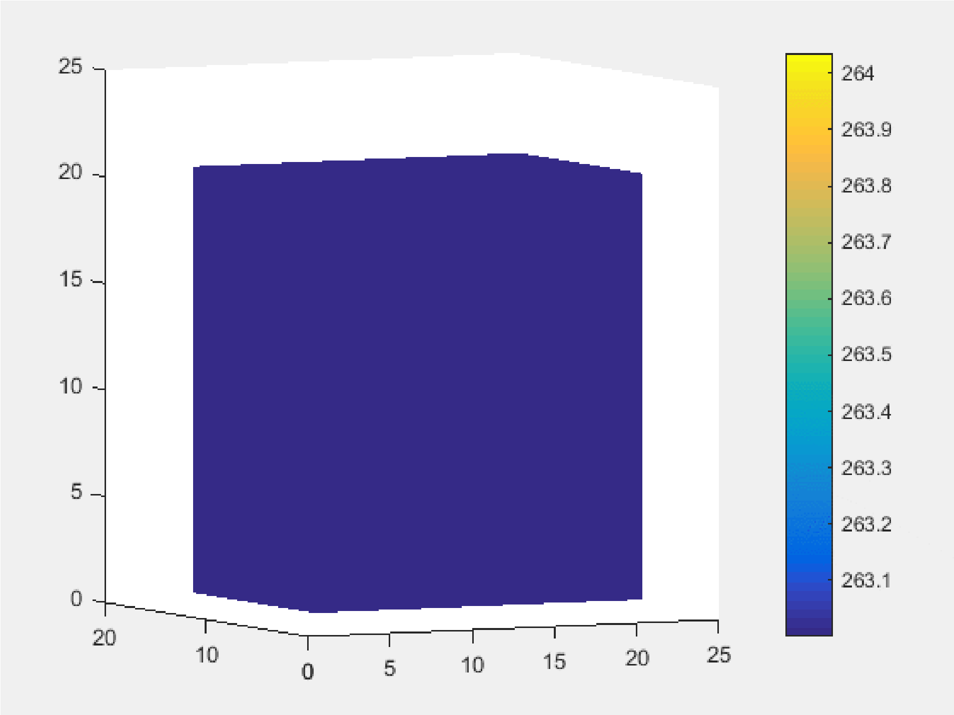

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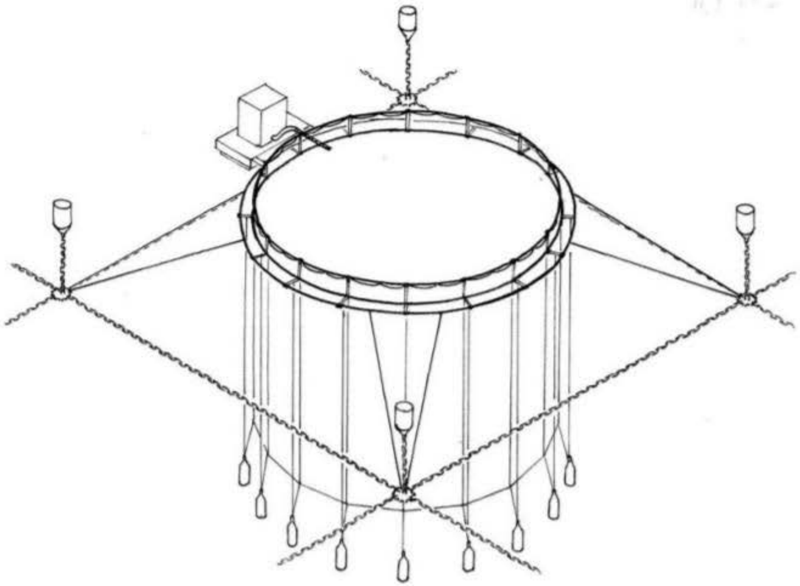
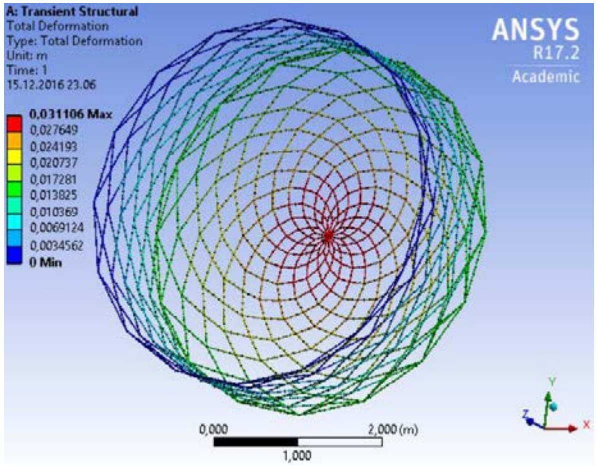
FISH CAGE





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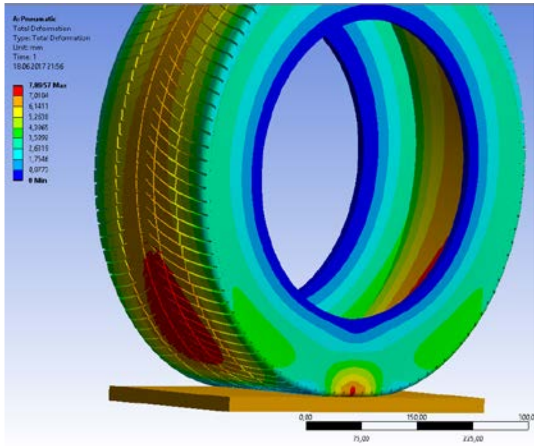

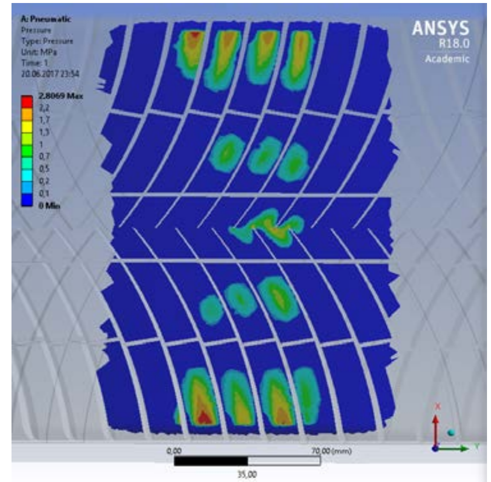

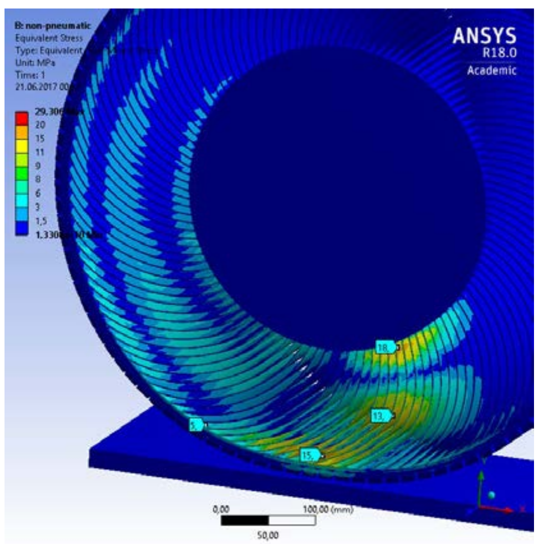

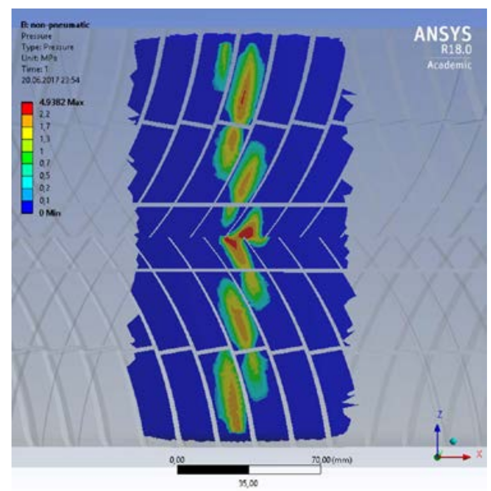

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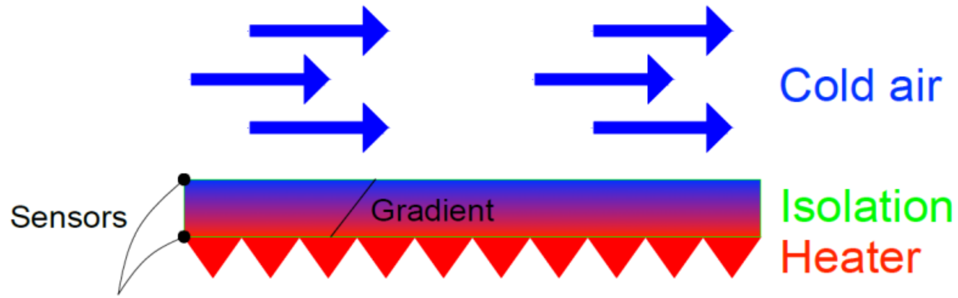
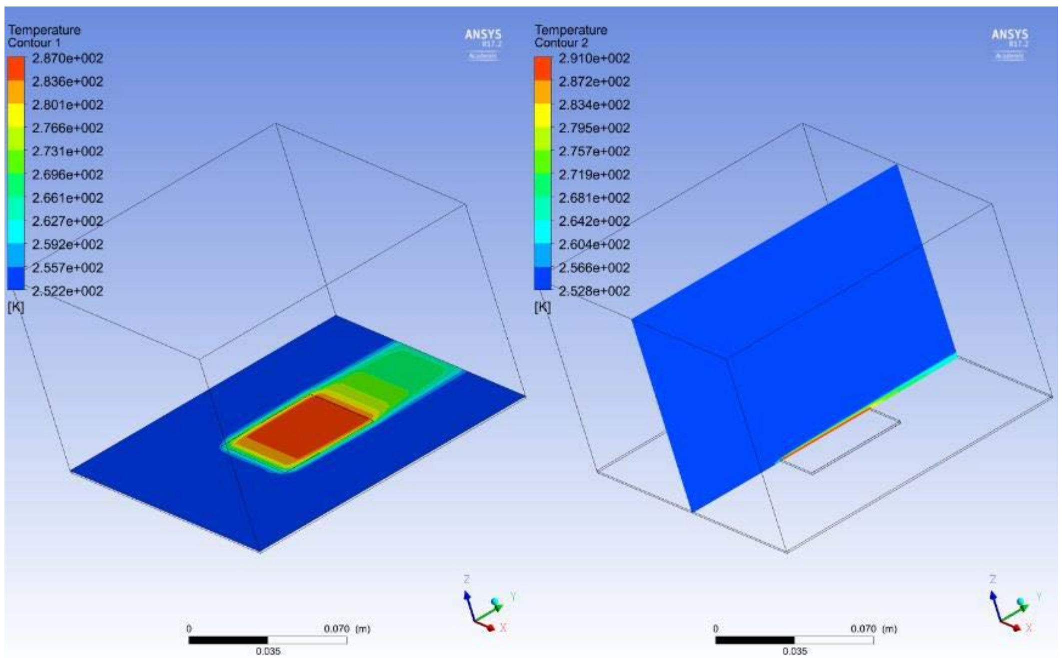
CONJUGATE HEAT TRANSFER





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POSSIBLE FUTURE WORK?

- PLASMA (EXAMPLE: FUSION REACTION)
  - CFD Modelling of Plasma

	Magnetohydrodynamics	Two Fluids	Gyrokinetics	Kinetics	Everything
Description	The plasma is one continuous fluid - ions have all the mass, but electron carry all the current.	Break the ions & electrons into two continuous, mingling fluids.	Only track superparticles' straight motion - and ignore the corkscrewing.	Assign particles a speed and location based on a distribution. Track super particles through space.	Track every particle, at all times.
Strengthens	Easily solved.	Simple bulk effects like drift waves & reconnection can be understood.	Captures most of kinetic model, but much easier to solve - can model an entire Tokamak.	Many things captured, can get powerful results like the linear velocity-space instabilities.	Most accurate model possible.
Weakness	Most things not captured: most plasma waves, leakage, kinetic instabilities, structures etc.	Many things not captured: plasma instabilities, large effects & non-equilibrium effects. Assumes bell curves.	Non-physical behavior over long times: resonances & adiabatic invariants can be lost.	Tough to solve: hard to apply to full-size reactors. Loses some effects: like plasma microdensity and collective thomson scattering.	Typically impossible to solve.
Mathematics	Navier-stokes, Lorentz force, Maxwells' equations.	Navier-stokes, Lorentz force, Maxwells' equations.	Vlasov-Maxwell Expansion Equation	Vlasov-Maxwell Equation	Klimontovich Model

Plasma as a fluid (Chalkboard) — Magnetohydrodynamics, Two Fluids

Plasma as a gas (Computer Required) — Gyrokinetics, Kinetics, Everything

Source: Wikipedia: Plasma Modeling

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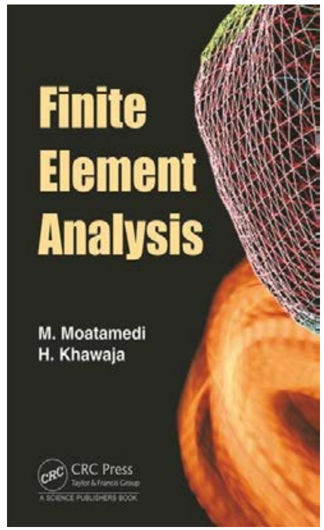

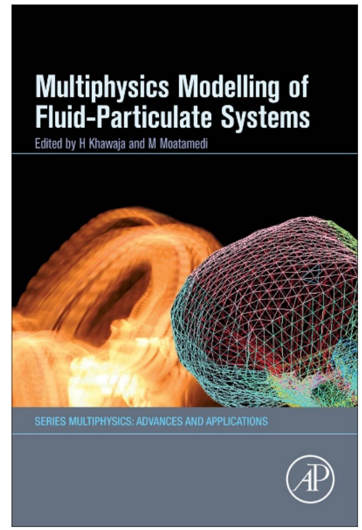

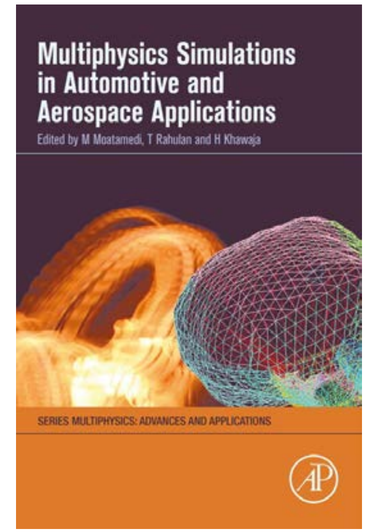

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