Chapter 2
Introduction to Modern Measuring Techniques of Thermal Fluid Mechanics

Prof. Dr.-Ing An-Bang Wang
（王安邦，臺大特聘教授）
Institute of Applied Mechanics
National Taiwan University
TEL: 886-2-3366-5067
E-mail: abwang@spring.iam.ntu.edu.tw

Course Contents

- **Term project introduction & assignment (2/24)**
- **Introduction to modern measuring techniques of thermal fluid mechanics (3/3, 3/10)**
- **How to visualize your flow? (3/10, 3/17, 3/24, 3/31)**
- **1st Mid-term discussions (4/21)**
- **How to design and set up your experimental facility? (4/7, 4/14, 4/28, 5/05)**
- **How to quantitatively measure your system? (5/12, 5/19, 5/26, 6/02)**
- **2nd Mid-term discussions (5/26)**
- **Miscellaneous measurements (viscosity, surface tension, density, refractive index, thermal conductivity …etc.) (6/09, 6/16)**
- **Final Presentation & report (6/23)**

Lecture Contents of Chapter 2

- What & Why thermal fluid mechanics ?
- Tools for solving problems
- The needs and design of modern measuring techniques of Thermal Fluid Mechanics
- Dimensional analysis & Π-theorem
- Modelling and Similarity
- Accuracy Analysis

What do you think?

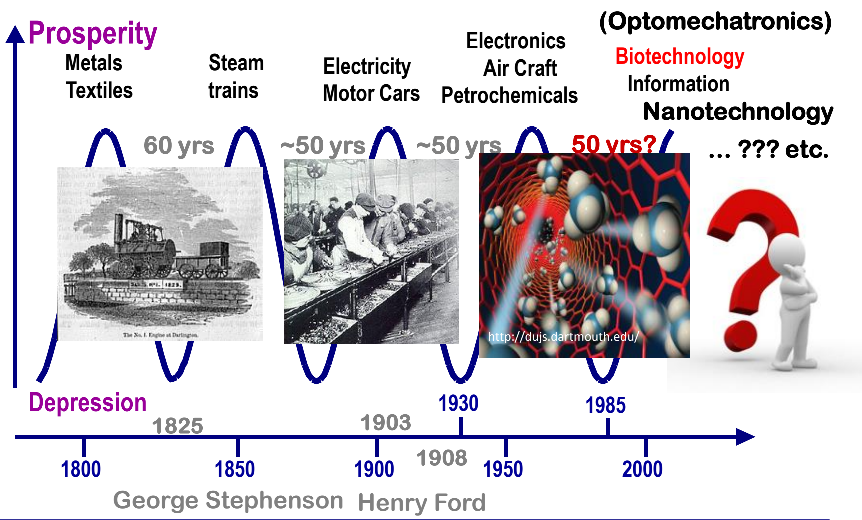
- (2021/02/25 中時新聞網)理組 選？台大生示警：必修課看到「這2字」

https://www.chinatimes.com/realtimenews/20210225006161-260405?chdtv

現代熱流量測技術

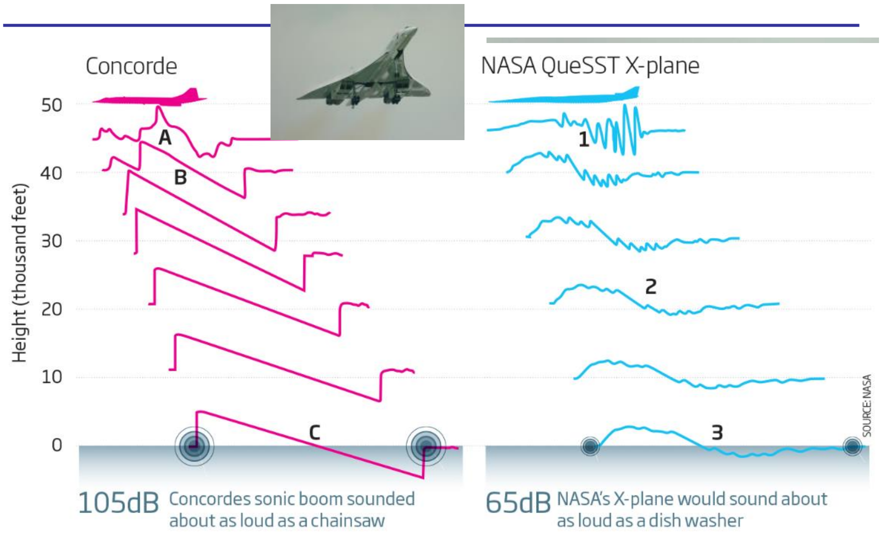
(Modern Measuring Techniques of Thermal Fluid Mechanics)

Trend of the world



What & Why Thermal Fluid Mechanics?

Flow Examples: Supersonic Airliner



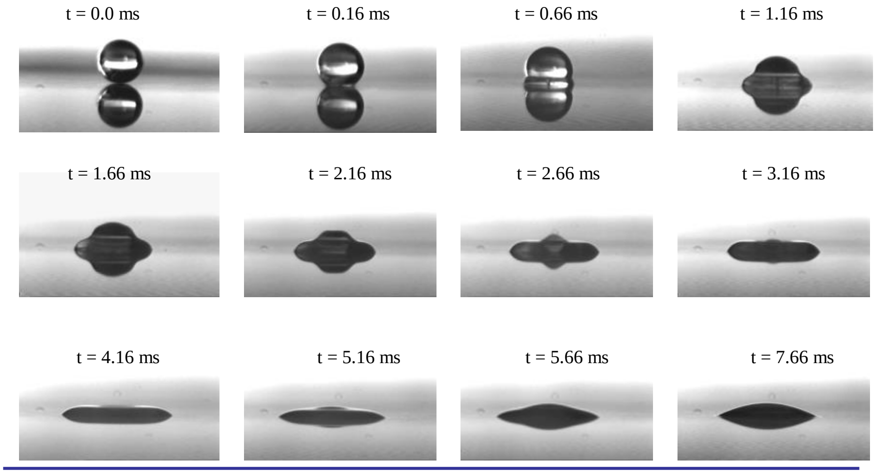
Thermal related Examples:

- Influence of 《**±2**℃》 (2010年2月22日發布)
- **Human body temperature**: Normal: 37**±0.5**℃
  (Ex: 中醫臨床的研究《算病》樓中亮中醫預防保健APP)
- Processing control in **chemical** engineering
- Processing control in **mechanical** engineering
- Processing control in **food** engineering
- Processing control in **agriculture**
- In many other process …

- **Example of drop impact:**

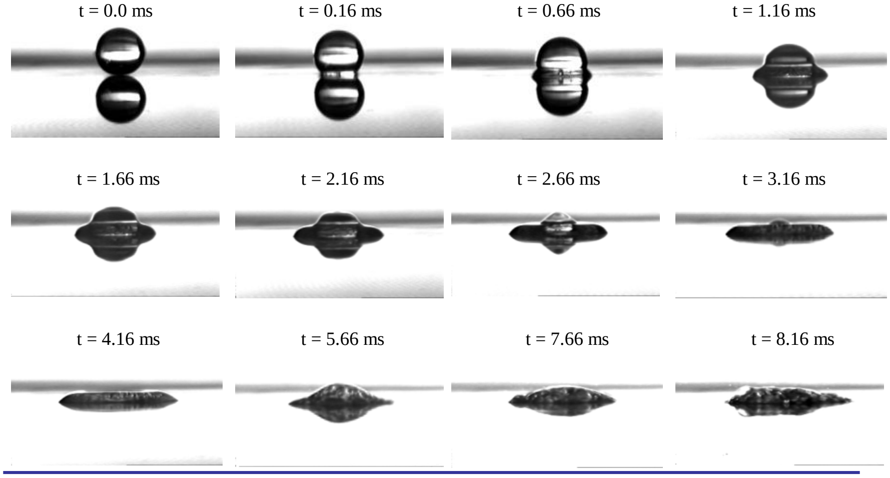
Drop Impact Pattern (I) Completely Wet

(Ethanol, D_p=550µm；Re=189；We=8.65；T_w=23℃)

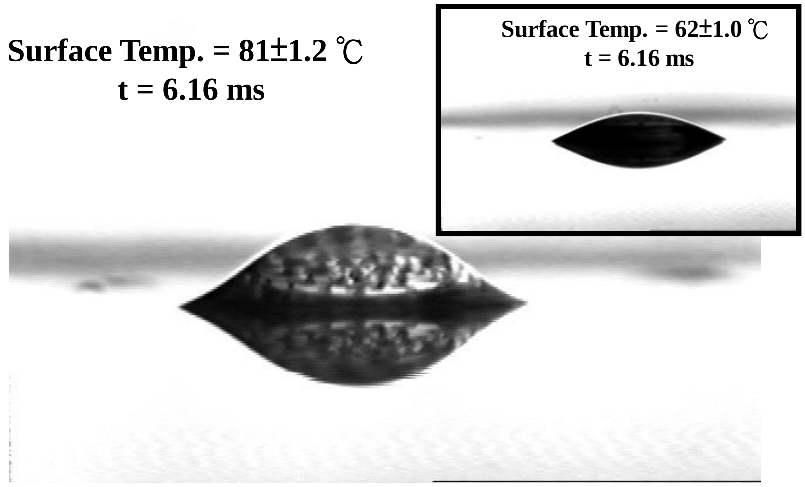


Drop Impact Pattern (II) Wet Boiling

(Ethanol, D_p=550µm；Re=189；We=8.65；T_w=81℃)

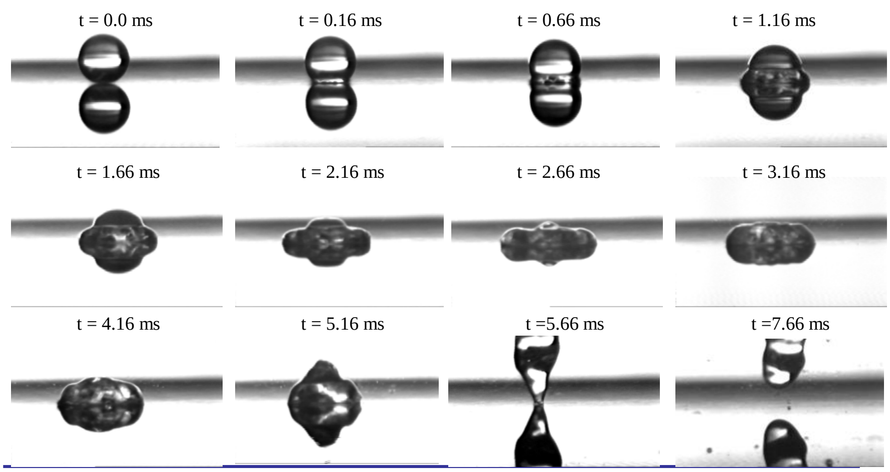


A Close Look of Bubble Generation



Drop Impact Pattern (III) Transition

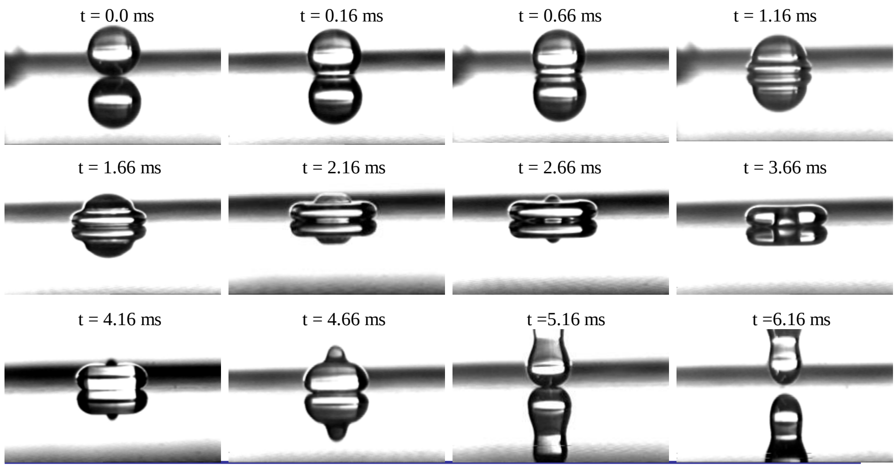
(Ethanol, D_p=550µm；*Re*=189；*We*=8.65；T_w=116℃)



Modern Measuring Techniques of Thermo-fluids Mechanics
By An-Bang Wang
National Taiwan University Institute of Applied Mechanics

Drop Impact Pattern (IV) Dry Rebounding

(Ethanol, D_p=550μm；Re=189；We=8.65；T_w=130℃)



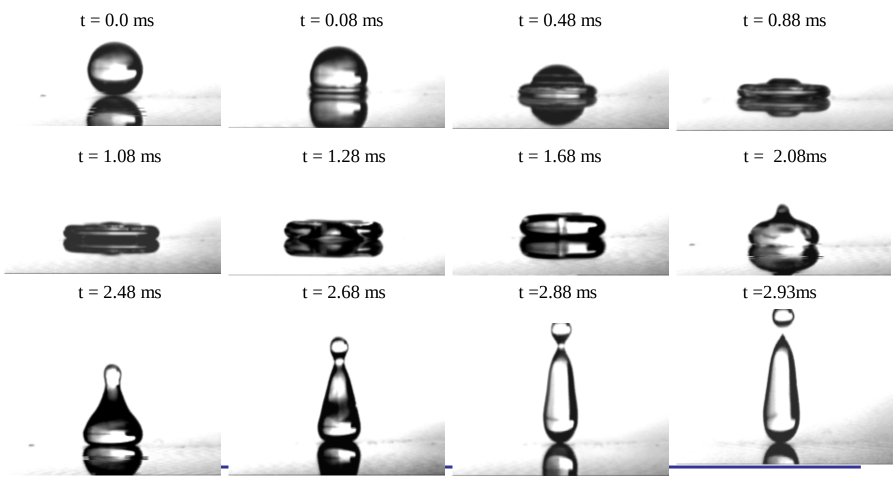
Modern Measuring Techniques of Thermo-fluids Mechanics

By An-Bang Wang

National Taiwan University Institute of Applied Mechanics

Drop Impact Pattern (V) Satellite Dry Rebounding

(Ethanol, D_p=550μm；Re=881；We=188.33；T_w=138℃)



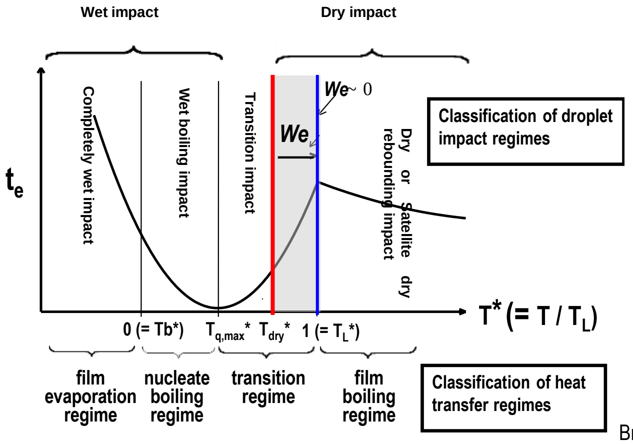
Modern Measuring Techniques of Thermo-fluids Mechanics

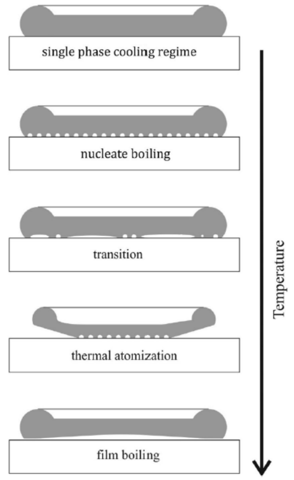
By An-Bang Wang

National Taiwan University Institute of Applied Mechanics

Classification of drop impact regimes

Wang et al., Physics of Fluids (2000/06)





Breitenbach et al. Exp. Fluids (2018)

Modern Measuring Techniques of Thermo-fluids Mechanics

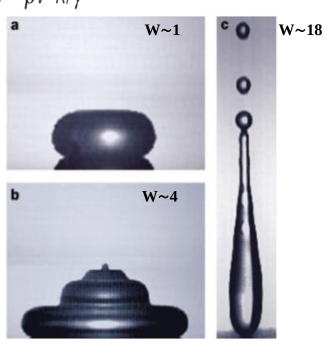
By An-Bang Wang

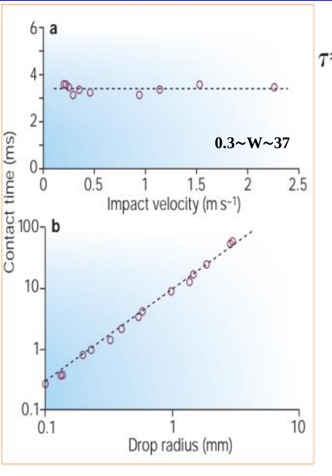
National Taiwan University Institute of Applied Mechanics

Contact time of a bouncing drop

Denis Richard*, Christophe Clanet†, David Quéré **NATURE** | VOL 417 | 2002

$W = \rho V^2 R / \gamma$





$\tau \approx (\rho R^3 / \gamma)^{1/2}$

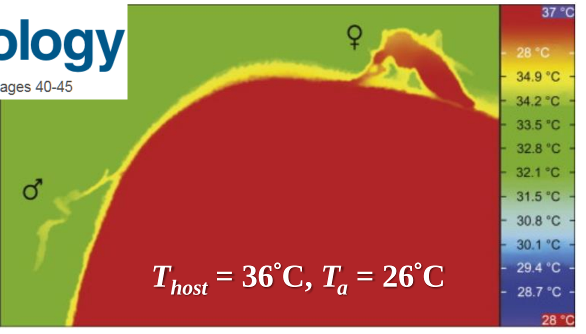
The contact time is independent of the details of the impact.

The contact time does not depend on the impact over a wide range of velocities. (20 – 230 cm/s)

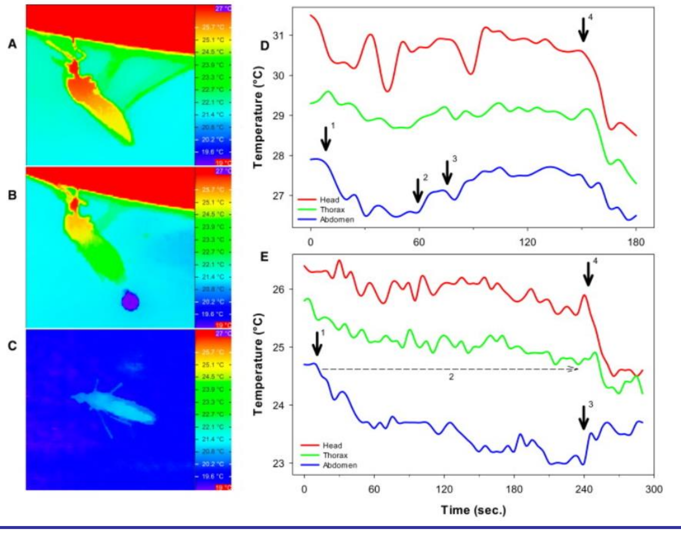
Temperature Control of animals

- 吸血維生的蚊蟲都是大胃王。**蚊子**在飽足一頓血之後，體型可以變成進食前的兩到三倍大；**壁蝨、錐鼻蟲**，進食後更是可以脹大十倍至一百倍。(https://case.ntu.edu.tw/blog/?p=30156)
- 節肢動物是變溫動物 (環境溫度等於體溫) 。蚊子吸完血之後，體溫可以在一分鐘內急速上升攝氏 10 到 15 度。

Current Biology
Volume 22, Issue 1, 10 January 2012, Pages 40-45



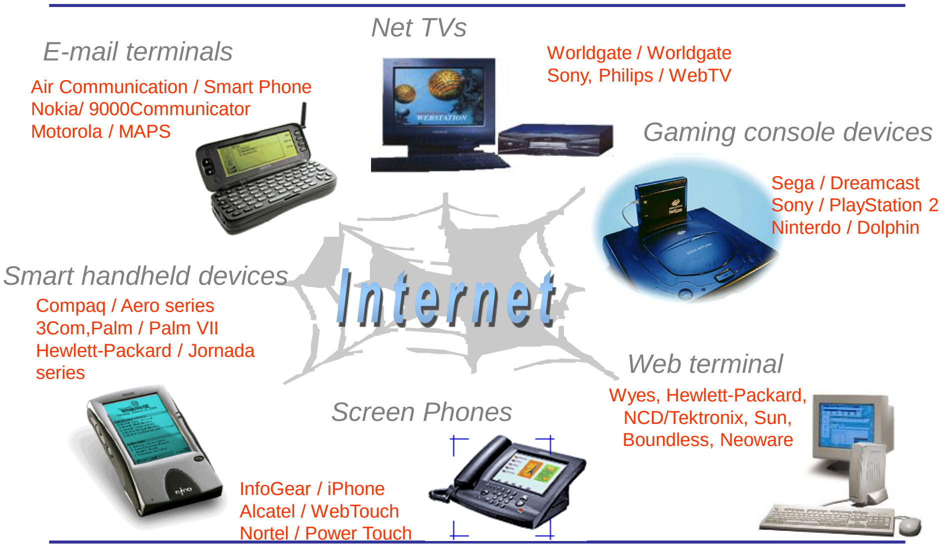
Temperature Control of animals



What did you learn?

- What are the difference between them (experiment in lab course and term-projects? High I.F.-journal and others?)
- Is the conducting process the same? Or different?
- Which one is simpler?
- What do you want to be?

IA-products



Thermal Solutions & Measurement

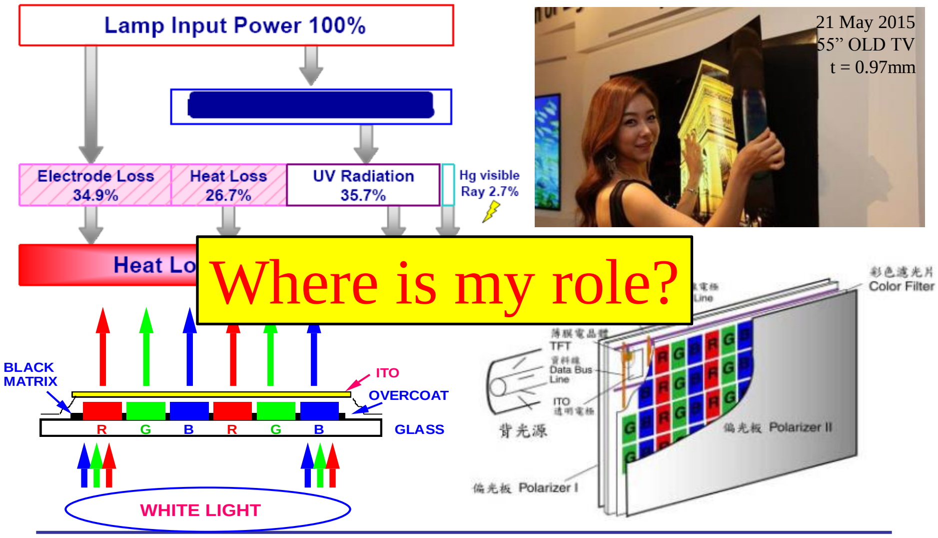
How to measure other flow properties?

影像顯示科技(*FPD Technology*)

- 視覺為五覺之首，是接受資訊與知識之大門

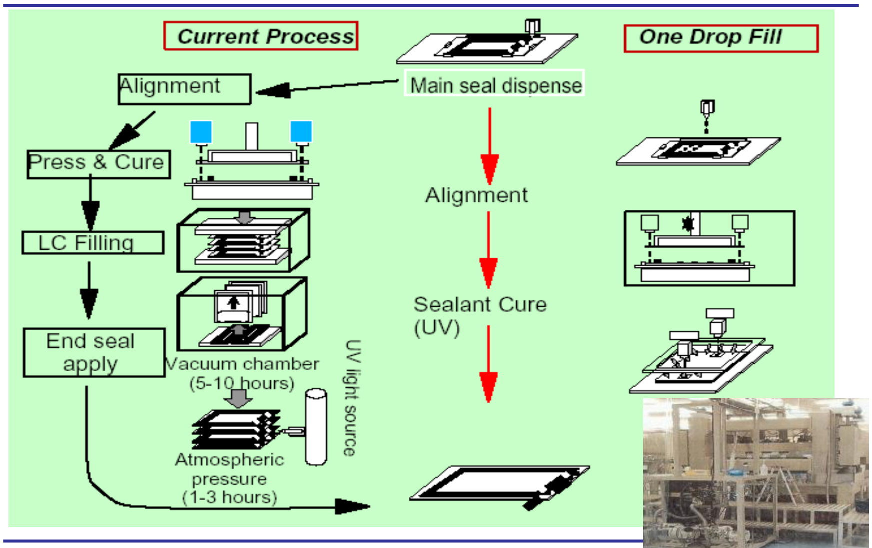
影像顯示科技
- 內涵 (數位內容)
- 外表
  - 軟顯示器
  - 硬顯示器

Display Technology



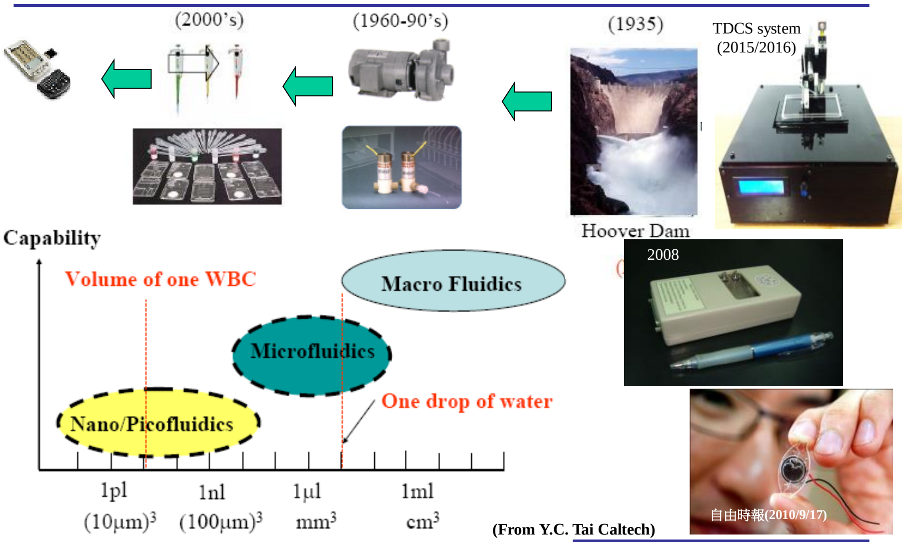
Where is my role?

Old Process & ODF for FPD Manufacture



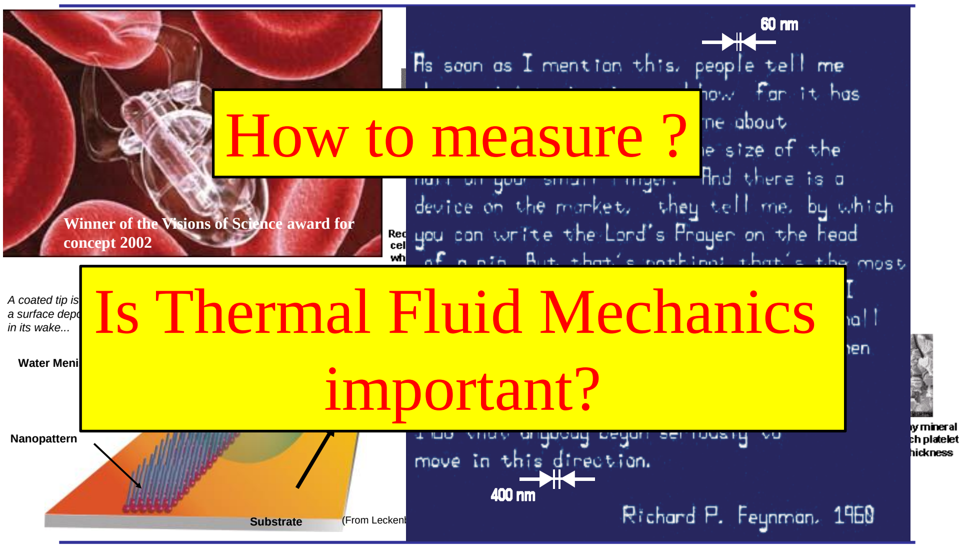
Bio-technology

Microfluidics and Microfluidic Platform



(From Y.C. Tai Caltech)

Nano-technology

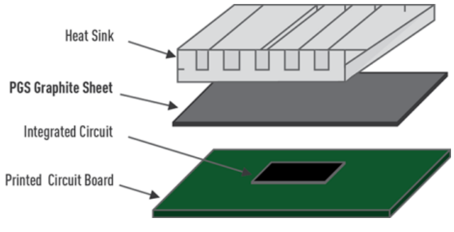


How to measure ?

Is Thermal Fluid Mechanics important?

Resource/Outsourcing from the market

- PGS: Pyrolytic Graphite Sheet
- Thermal conductivity: 700 to 1950 W/(m-K) (2- 5 times of copper [400W/(m-K)] , 3 - 8 times of aluminum [237W/(m-K)])
- High stability (withstand up to 400˚C), no deterioration with age
- Simultaneous solution for thermal and electromagnetic wave problems
- Thin, flexible and easy to cut or trim
- Withstands repeated bending
- Low thermal resistance
- RoHS (Restriction of Hazardous Substances) and REACH compliant



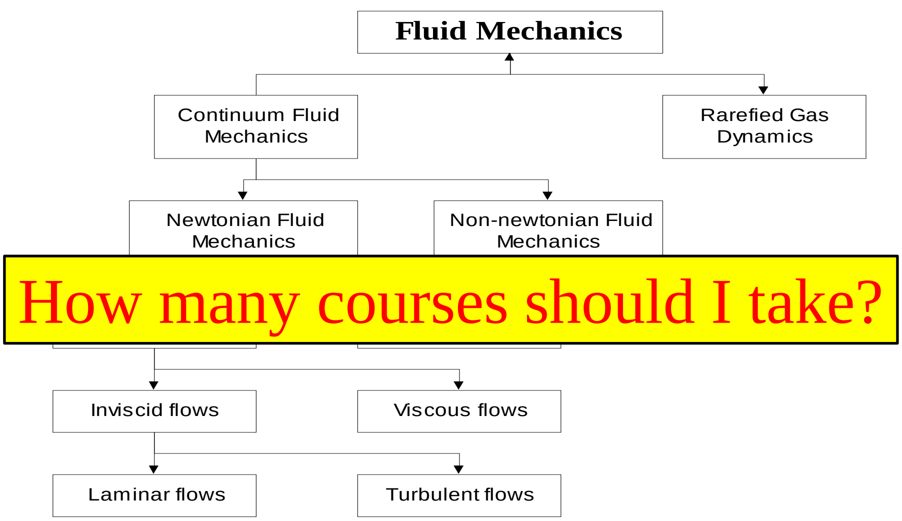
Courses of Thermal Fluid Mechanics/Science

- **Thermo-fluids, Thermal/Fluids, Thermal Fluid, …**
- **Thermal courses:**
  - **Thermal-Fluids Engineering I, II (MIT)**
  - **Thermodynamics**

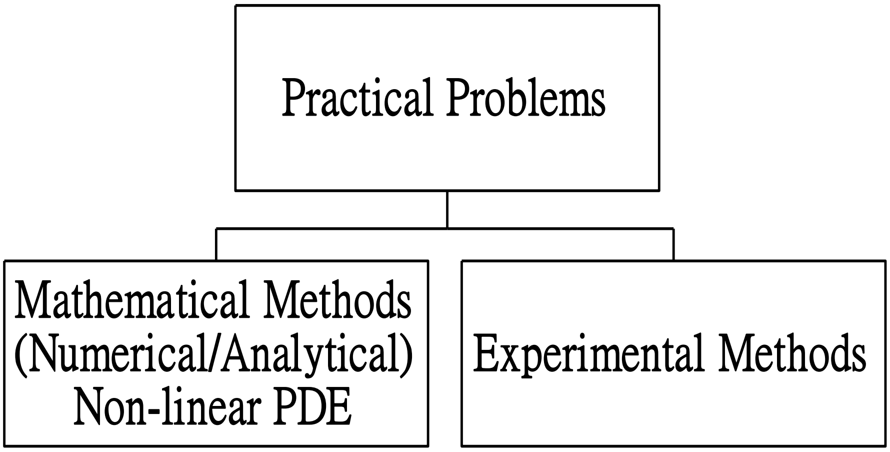
How about Fluid Mechanics courses?

  - **Transport Phenomena**
  - **Engineering Analysis**
  - **Mathematical Methods in Applied Mechanics**
  - **Advanced Thermodynamics**
  - …

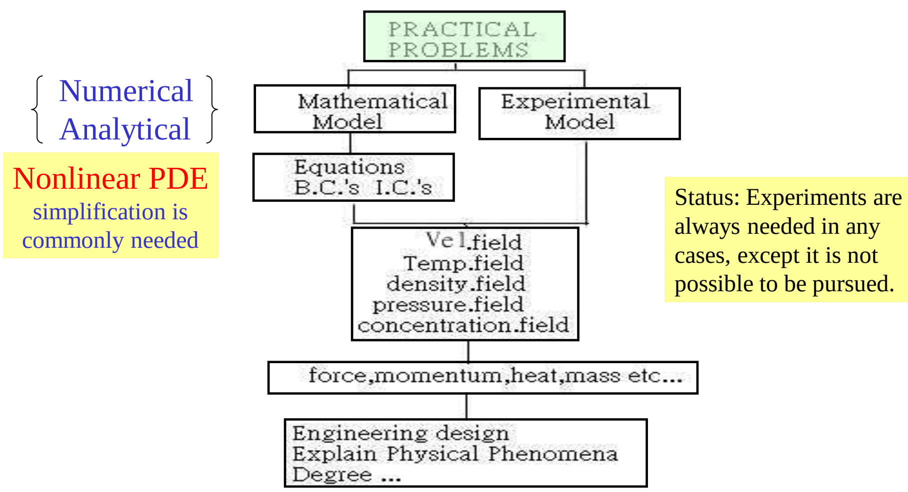
Scope of Fluid Mechanics



Tools for Solving Problems



Approaches to solve problems of Fluid Mechanics

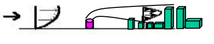
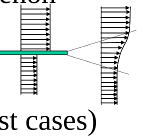


Experiments & Simulations

Speedo LZR Racer swimsuit

Why experiments ?

The need for experiments in fluid mechanics arises from a variety of aims :

- **Basic research**

  - Extend physical understanding of a particular flow phenomenon
  - Test new theoretical results
  - Verify numerical models (e.g. in CFD)

- **Model studies** (inexpensive compared to prototype tests in most cases)
  - Investigate an unknown flow situation or test new apparatus designs
  - conduct a systematic parameter study and/or optimization
  - establish scaling laws

- **Flow Measurement**
  - E.G. Volume flow rate, drag, lift ...etc
  - Measurement of a quantity for control feedback purposes.

Modern Measuring Techniques of Thermo-fluids Mechanics

By An-Bang Wang

National Taiwan University
Institute of Applied Mechanics

Design of an Experiment (I)

In designing an experiment, a number of questions must be asked :

- ***Which quantities*** are important to measure (both independent and dependent)?
  - This is answered partly through the ***aim of the experiment*** and partly through ***experience.***
  - ***Dimensional analysis*** is ***indispensable*** for complex systems.
- In ***what range*** will the measured quantities vary ?
  - This information,and information about the required accuracy is necessary for the choice of measuring technique.
- Which quantities must be controlled ?
  --operating conditions must be well defined in order to control the experiments to be ***repeatable, stationary*** and simulated to the given conditions.

Design of an Experiment (II)

- What is the required **dynamic response** of the measuring instrument?
  - Is any correction or compensation necessary ?
- What is the **measurement time** ?
  - For time mean averaged quantities, a given statistical variance should be specified.
- Has this experiment already been performed ?
- Does a theoretical solution exist ?

Check points I : *How about my case?*

- ***Have I a clear topic to start in this?***
- Has this experiment already been performed ?
- Does a **theoretical solution** exist ?
- What is my ***novelty***?

Dimensional analysis

Dimensional analysis facilitates the interpretation and extends the range of application of experimental data by correlating them in terms of dimensionless groups. Its most serious limitation is that it gives ***no*** information about the nature of a phenomenon. Rather it is necessary to know before hand which variables influence the phenomenon.

Typically ,the primary dimensions are chosen as

- M : mass
- L :length
- T :time
- θ: temperature

Why dimensional analysis (I)?

Dimensional analysis (***DA***) is enormous time- and money-saving !
Example: force on an immersed body

$$F = f(L, V, \rho, \mu)$$

generally speaking , we need 10 experimental points to define a curve, this means that we need

$$10*10*10*10=10^4 \text{ experiments.}$$

assuming NT $10 /experiment we need 10^5 NT - dollars
and 0.1 day /experiment, we need 10^3 days =2.7years !!!
However , by using ***DA***

$$C_f = F/\rho V^2 L^2 = g(\rho VL/\mu) = g(Re)$$

Nothing is lost , but with
NT $ 10 /experiment x 10 experiments =100 NT-dollars
and 0.1 day /experiment x 10 exp. = 1 day!!
It's a big difference !

Why dimensional analysis (II)?

2. ***DA*** helps thinking and planning (not only experiment but also theory)!
   It suggest variable which can be discarded and often give a great deal of insight into the form of the physical relationship .
3. ***DA*** provides ***scaling law*** (or similarity) which may convert data from a cheap, small model into design information for an expensive ,large prototype.

- A method for describing dimensionless parameter is generally credited to E. Buckingham in 1914, and is commonly called "***Buckingham Π-theorem***".
- From the governing Equations, boundary conditions, we may also get the governing dimensionless parameters

Dimensionless Groups in Fluid Mechanics (I)

Parameter	Definition	Qualitative ratio of effects	Importance
Reynolds number	$\mathrm{Re} = \frac{\rho U L}{\mu}$	$\frac{\text{Inertia}}{\text{Viscosity}}$	Always
Mach number	$\mathrm{Ma} = \frac{U}{a}$	$\frac{\text{Flow speed}}{\text{Sound speed}}$	Compressible flow
Froude number	$\mathrm{Fr} = \frac{U^2}{gL}$	$\frac{\text{Inertia}}{\text{Gravity}}$	Free-surface flow
Weber number	$\mathrm{We} = \frac{\rho U^2 L}{\Upsilon}$	$\frac{\text{Inertia}}{\text{Surface tension}}$	Free-surface flow
Cavitation number (Euler number)	$\mathrm{Ca} = \frac{p - p_v}{\rho U^2}$	$\frac{\text{Pressure}}{\text{Inertia}}$	Cavitation
Prandtl number	$\mathrm{Pr} = \frac{\mu c_p}{k}$	$\frac{\text{Dissipation}}{\text{Conduction}}$	Heat convection
Eckert number	$\mathrm{Ec} = \frac{U^2}{c_p T_0}$	$\frac{\text{Kinetic energy}}{\text{Enthalpy}}$	Dissipation
Specific-heat ratio	$\gamma = \frac{c_p}{c_v}$	$\frac{\text{Enthalpy}}{\text{Internal energy}}$	Compressible flow

White (1986)

Dimensionless Groups in Fluid Mechanics (II)

Parameter	Definition	Qualitative ratio of effects	Importance
Strouhal number	$\mathrm{St} = \frac{\omega L}{U}$	$\frac{\text{Oscillation}}{\text{Mean speed}}$	Oscillating flow
Roughness ratio	$\frac{\epsilon}{L}$	$\frac{\text{Wall roughness}}{\text{Body length}}$	Turbulent, rough walls
Grashof number	$\mathrm{Gr} = \frac{\beta \Delta T g L^3 \rho^2}{\mu^2}$	$\frac{\text{Buoyancy}}{\text{Viscosity}}$	Natural convection
Temperature ratio	$\frac{T_w}{T_0}$	$\frac{\text{Wall temperature}}{\text{Stream temperature}}$	Heat transfer
Pressure coefficient	$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U^2}$	$\frac{\text{Static pressure}}{\text{Dynamic pressure}}$	Aerodynamics, hydrodynamics
Lift coefficient	$C_L = \frac{L}{\frac{1}{2}\rho U^2 A}$	$\frac{\text{Lift force}}{\text{Dynamic force}}$	Aerodynamics, hydrodynamics
Drag coefficient	$C_D = \frac{D}{\frac{1}{2}\rho U^2 A}$	$\frac{\text{Drag force}}{\text{Dynamic force}}$	Aerodynamics, hydrodynamics

Buckingham π-theorem

Process :

1. list down the all variables involved in the problem

(n = ?) $F(B_1, B_2, B_3, \ldots\ldots B_n) = C$ (Most critical and difficult process!)

2. choose the primary j variables, which cover the whole needed dimensions, but do not form a π-product

(j = ?) $B_1, B_2, B_3, \ldots, B_j$ (In fluid mechanics M, L, T, Θ!)

3. Add each additional variable to your j variables to form a power product, then find the exponents which make the n-j product dimensionless ,

$$\Pi_1 = B_1^{a1,1} B_2^{a1,2} \ldots\ldots B_j^{a1,j}\, B_{j+1}$$
$$\Pi_2 = B_1^{a2,1} B_2^{a2,2} \ldots\ldots B_j^{a2,j}\, B_{j+2}$$
$$\Pi_{n-j} = B_1^{an-j,1} B_2^{an-j,2}\, B_j^{an-j,j}\, B_n$$

4. we get finally $F_1(\Pi_1, \Pi_2, \ldots\ldots \Pi_{n-j}) = C_1$

(the reduction of variables : j)

Example of Buckingham π-theorem (I)

Consider the problem of pressure drop in steady pipe flow

(1) $F = F(\Delta p, V, L, D, \rho, \mu, e) = C$ ⇦ n = 7

(2) choose primary j variables: V, D, ρ ⇦ j = 3

(Which one is better? It's a matter of taste, custom and user's choice.)

(3) Find the n-j Π: ⇦ n-j = 7-3 =4

$$\Pi_1 = V^{a1,1} D^{a1,2} \rho^{a1,3}\, \Delta p$$
$$\Pi_2 = V^{a2,1} D^{a2,2} \rho^{a2,3}\, L$$
$$\Pi_3 = V^{a3,1} D^{a3,2} \rho^{a3,3}\, \mu$$
$$\Pi_4 = V^{a4,1} D^{a4,2} \rho^{a4,3}\, e$$

$$\Pi_1 = V^{a1,1} D^{a1,2} \rho^{a1,3}\, \Delta p$$

Example of Buckingham π-theorem (II)

$$\Pi_1 = M^0L^0T^0 = V^{a1,1}D^{a1,2}\rho^{a1,3}\,\Delta p$$

$$= (LT^{-1})^{a1,1}(L)^{a1,2}(ML^{-3})^{a1,3}\,(ML^{-1}T^{-2})$$

for M: $0 = a1,3 + 1$

L: $0 = a1,1 + a1,2 - 3 \times a1,3 - 1$

T: $0 = -a1,1 - 2$

so that $a1,1 = -2,\ a1,2 = 0,\ a1,3 = -1$

$$\Pi_1 = M^0L^0T^0 = V^{-2}D^0\rho^{-1}\,\Delta p = \Delta p/\rho V^2$$

Similarly, $\Pi_2 = L/D$, $\Pi_3 = \mu/\rho VD$ (= Re), $\Pi_4 = e/D$

$\Rightarrow F_1(\Pi_1, \Pi_2, \Pi_3, \Pi_4) = F_1(\Delta p/\rho V^2, L/D, \mu/\rho VD, e/D) = C_1$

or $\boxed{\Delta p/\rho V^2 = F2(L/D, \mu/\rho VD, e/D)}$

However, DA says nothing about the functional form of F1 or F2!!

Modelling and Similarity

$$\Pi_1 = F(\Pi_2, \Pi_3, \ldots\ldots \Pi_k)$$

model $\qquad \Pi_{2m} = \Pi_{2p} \qquad$ prototype

$$\Pi_{3m} = \Pi_{3p}$$

$$\ldots \qquad \ldots$$

$$\Pi_{km} = \Pi_{kp}$$

$\Rightarrow \Pi_{1m} = \Pi_{1p} \Rightarrow$ Complete Similarity

But in engineering, instead of complete similarity, We consider:

Geometric similarity (L-scale)

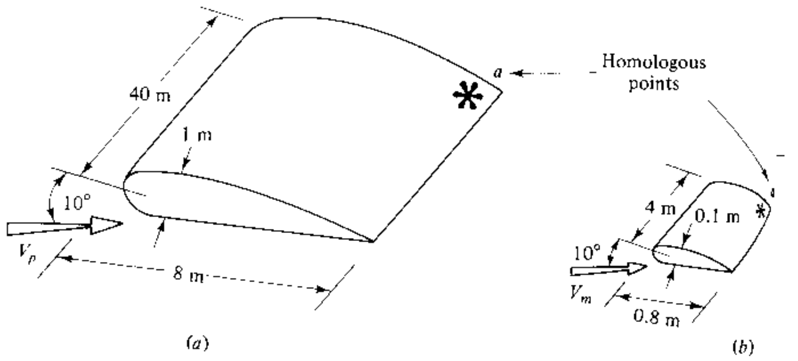
Kinematic similarity (L- & t-scale)

Dynamic similarity (L- & t- & m-scale)

(Thermal similarity)

Geometric Similarity

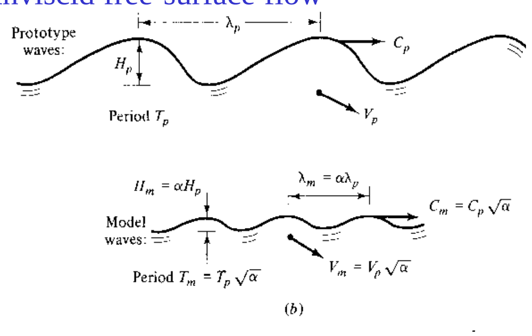
Geometric Similarity:
It requires all body dimensions in all three coordinates have the same linear scale ratio



Kinematic Similarity

Kinematic Similarity
It requires the model and prototype have the same length-scale ratio (geometric similarity) and also the same time scale ratio

Inviscid free-surface flow



$\lambda_m/\lambda_p = \alpha = H_m/H_p$

since $Fr_m = Fr_p$

$V_m^2/g\lambda_m = V_p^2/g\lambda_p$

⇨ $V_m/V_p = (\lambda_m/\lambda_p)^{1/2}$

$= \alpha^{1/2} = \beta$

α & β are dependent!

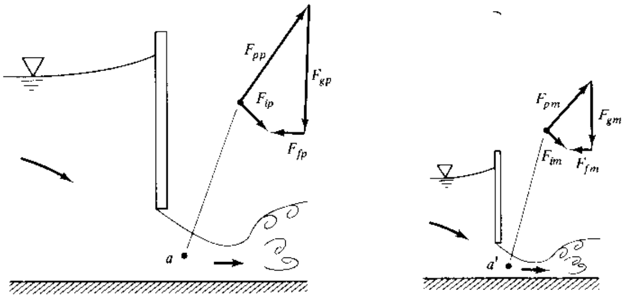
also $c_m/c_p = \alpha^{1/2}$

period: $T_m/T_p = \alpha^{1/2}$

Modern Measuring Techniques of Thermo-fluids Mechanics
By An-Bang Wang
National Taiwan University Institute of Applied Mechanics

Dynamic Similarity

•Dynamic Similarity
It requires the same ***length-scale ratio***, ***time scale ratio*** and also ***force-scale ratio***



$$F_{p(ressure)} + F_{g(ravity)} + F_{f(riction)} = F_{i(nertia)}$$

$Fr_p = Fr_m$ $\quad Re_p = Re_m$

Discrepancies in model-prototype similarity (I)

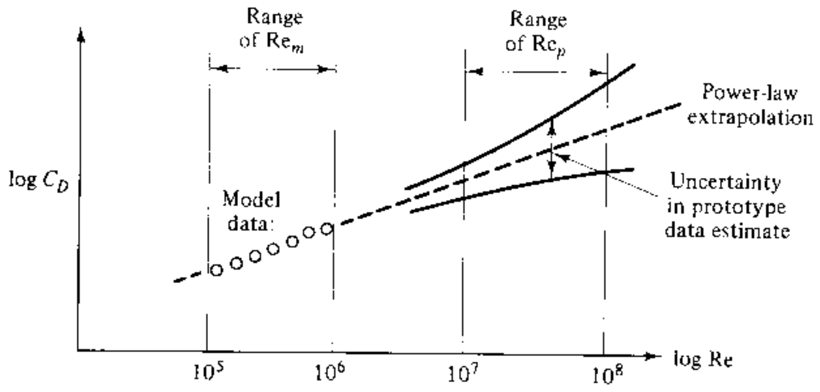
- The perfect dynamic similarity is more of a dream than a reality because true equivalence of characteristic dimensionless parameters can be achieved only by dramatic changes in fluid properties , whereas in most model testing is simply done with air and water, the cheapest fluids available.
- Example: consider hydraulic model testing with free surface:
  Geometric similarity:
  $\lambda_m / \lambda_p = \alpha = 1/10$
  Froude number (Fr):
  $V_m^2/g\lambda_m = V_p^2/g\lambda_p \Rightarrow V_m/V_p = (\lambda_m/\lambda_p)^{1/2} = \alpha^{1/2} = 0.32$
  Reynolds number (Re):
  $V_m\lambda_m/\nu_m = V_p\lambda_p/\nu_p \Rightarrow \nu_m/\nu_p = (\nu_m/\lambda_p)^{3/2} = \alpha^{3/2} = 0.032$

$\nu_p = 1\ mm^2/s$ for water ($\nu_{mercury} = 0.12\ mm^2/s$)

⇨ Re-similarity is unavoidably violated!!

Discrepancies in model-prototype similarity (II)

In practice, water is used for both model and prototype!



Check points II: What is my case?

For my experiment

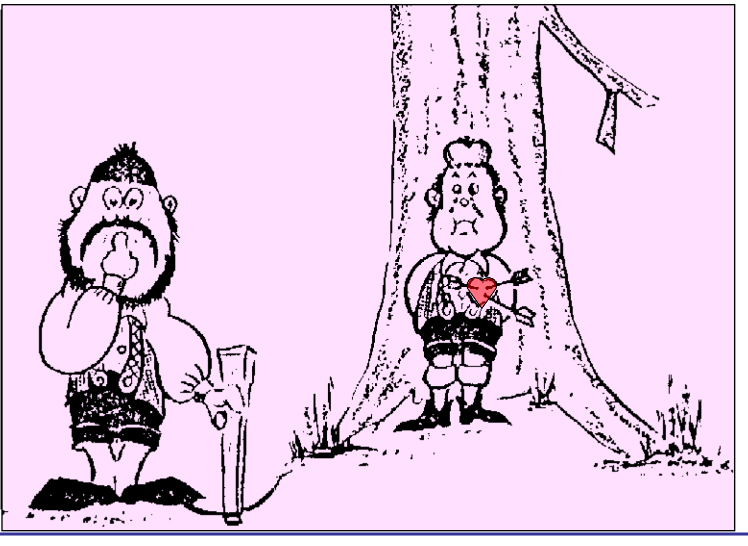
- ***Which quantities*** are important to measure (both independent and dependent)?
- Which quantities must be controlled ?
- In ***what range*** will the measured quantities vary? (Dynamic/Kinematic/Geometric Similarity?)
- What is the required **dynamic response** of the measuring instrument?
- How to determine the **measurement time**?

Terminology for Error Analysis

Terminology

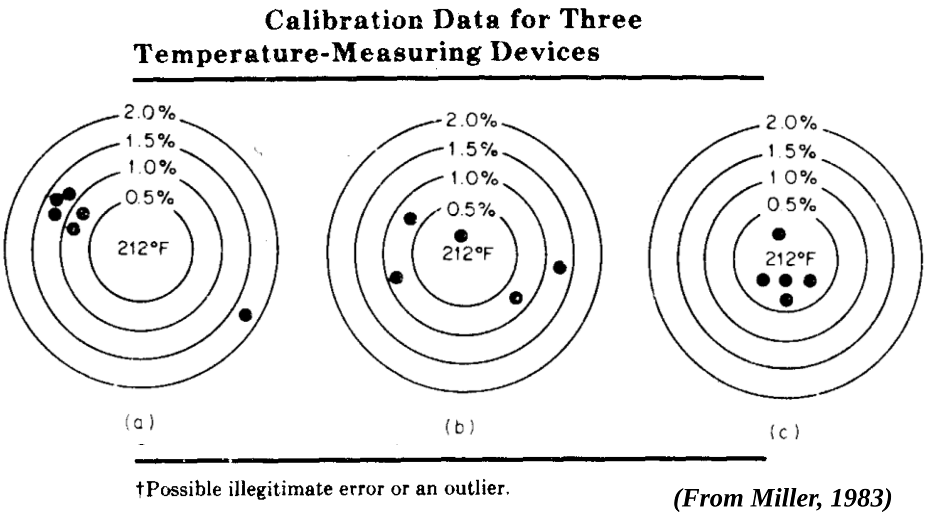
- ***Error***: deviation of the reading from a known input
- ***Accuracy***: Error, usually expressed as a percentage of full-scale reading.for industrial or laboratory instruments.
- ***Uncertainty***: range within the error is likely to fall with specified confidence limits (or fiducial limit).
- ***Precision*** (Repeatability):
  - ***reproducibility*** of the reading for a given input.
  - an instrument can be precise, but ***not*** calibrated or misused
  - accuracy of an instrument cannot be better than its precision.
- ***Traceability***: The ability to trace the accuracy of a standard back to its ultimate source in the fundamental standards (e.g., NIST)
- ***Sensitivity*** : ratio of instrument output to input.

Precision(repeatability) & Accuracy



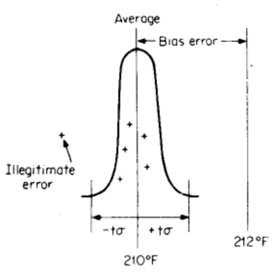
Modern Measuring Techniques of Thermo-fluids Mechanics *By An-Bang Wang* *National Taiwan University Institute of Applied Mechanics*

Precision, Bias error & Accuracy (I)



(From Miller, 1983)

Precision, Bias error & Accuracy (II)



(From Miller, 1983)

With the outlier omitted, the average of the reading

$\bar{I} = \frac{\sum I_i}{n}$ **=(210.1+210.0+209.8+210.2+209.9)/5=210.0**

the standard deviation is:

$\sigma = [\frac{\sum (I_i - \bar{I})/\bar{I})\times 100\%}{n-1}]^{0.5}$

=[(0.0023+0+0.0090+0.0090+0.0023)/(5-1)]$^{0.5}$ =0.0753%

∴ the *precision* at the 95% confidence level is then:

$\sigma_p = t_{st}\,\sigma$, where t_{st} is two-tailed student's t-value, could be found from table (t_{st} = 2.776 for n=5).

∴ the precision is then σ_p=2.776×0.0753%=0.21%

The *direction bias error* is

$B = \frac{\bar{I} - I_t}{I_t} \times 100\%$ **=[(210-212)/(212)] × 100%=-0.94%**

∴ the *accuracy* is $A_{cc} = B \pm \sqrt{(1+\frac{1}{n})}\sigma_p$ **=-0.7%~-1.2%**

Error Analysis (I)

- Almost all fluid flow measurements are indirect. (e.g. Pitot-tube for pressure, hot-wire for velocity ...)
- In experimental work, errors of two different types can occur :
  - Systematic Errors
    - poorly adjusted instruments
    - improper calibration
    - false instrument specification
    - incorrect or biased statistical estimators
  - Statistical or random errors
    - improper reading from a scale
    - statistical variance of the measured quantity.
- Some errors can be corrected or controlled, others (uncertainty) cannot. All must be estimated !

Error Analysis (II)

- The influence of the errors on the end result can be determined using the error propagation rule from Gauss , i.e. ,
  A quantity $\Phi = f(P_1, P_2 \ldots)$ dependent on individual parameters P_i,and with individual uncertaintiesδ_{pi}, the uncertainty $\delta\Phi$ could be written as

$$\delta\phi = \{(\frac{\partial\phi}{\partial p_1}\delta p_1)^2 + (\frac{\partial\phi}{\partial p_2}\delta p_2)^2 + \ldots\}^{1/2}$$

  In applying this relation, Gaussian error distributions are assumed.

Error analysis (III)

The Prandtl tube is used to measure flow velocity:

$$U=\sqrt{\frac{2\Delta P R T_1 g}{P_1}}$$

$\Delta P=P_1-P_2$

Where

R:gas constant, P_1:stagnation pressure

T_1:gas temperature, g:acceleration due to gravity

The uncertainty in U becomes

$$\delta u=\{(\frac{1}{4}\frac{2RT_1 g}{(\Delta p)\,p_1})\delta\Delta p^2+(\frac{1}{4}\frac{2\Delta pRT_1 g}{p_1^{\,3}})\delta p_1^{\,2}+(\frac{1}{4}\frac{2\Delta pRg}{p_1 T_1})\delta T_1^{\,2}\}^{1/2}$$

The normalized uncertainty is then

$$\frac{\delta u}{u}=\{(\frac{1}{2}\frac{\delta(\Delta p)}{\Delta p})^2+(\frac{1}{2}\frac{\delta(p_1)}{p_1})^2+(\frac{1}{2}\frac{\delta(T_1)}{T_1})^2\}^{1/2}$$

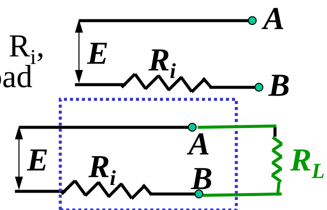
Clearly, a 0.1% accuracy in reading the temperature is not worthwhile, if for instant the ΔP can only be determined with 5% accuracy !

Some notes for electronics

- Impedance Matching

It is continually necessary to connect various electronic instruments in different combinations

Every instrument has an internal resistance R_i, in series with an externally connected load resistance R_L ,



The voltage

$$E_{AB}=E\,\frac{R_L}{R_L+R_i}$$

- If E_{AB} is to be measured, R_L should be chosen **large (e.g. scopes)**.
- If power is to be transmitted

  $P = E_{AB}^2 / R_L$ or $P = E^2 R_L / (R_L+R_i)^2$

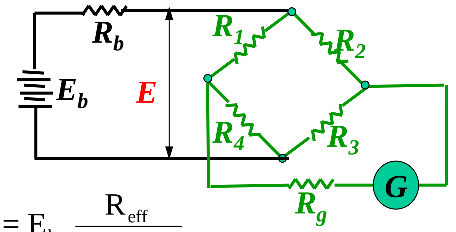
For a maximum transmission : $dP/dR_L=0$ then $R_L=R_i$

i.e. resistive part of impedance should be match.The inductive and capacitive terms must also be considered when dynamic response is important.

Wheatstone bridge

The Wheatstone bridge is a basic building block of many measuring instruments. It allows precise measurement of minute change in resistance, capacitance or inductance. It has many applications in

- hot-wire anemometry
- strain gauges
- Inductive pressure transducers or condenser microphones



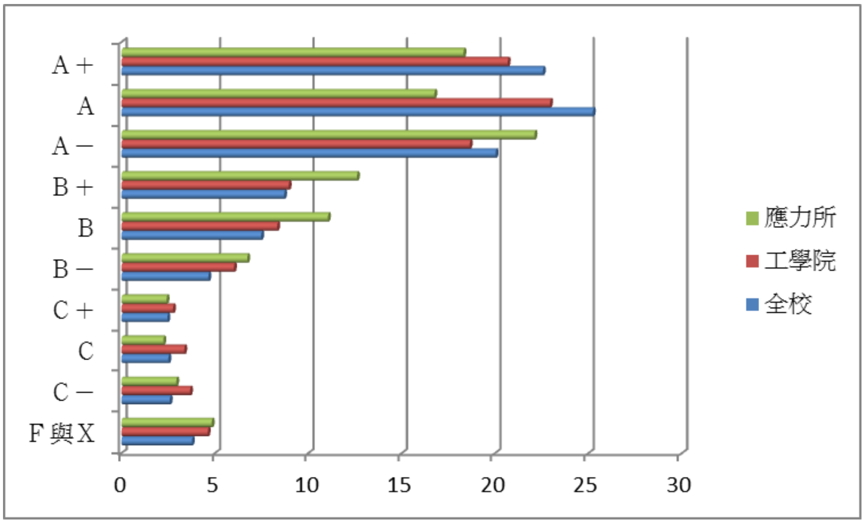
- effective bridge resistance:

$$R_{eff} = \frac{(R_1+R_4)(R_2+R_3)}{R_1+R_2+R_3+R_4} \quad , \quad E = E_b \frac{R_{eff}}{R_{eff}+R_b}$$

- Voltage measured at galvanometer:

$$E_g = E\left(\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3}\right)$$

Statistic score data of NTU



References (I)

- **Goldstein, S. (Ed.),** Modern Developments in Fluid Dynamics, Vol. I & II, Oxford University Press, London, 1952
- **Benedict, R.P.,** Fundamentals of temperature, pressure and flow measurements, 3rd Ed., John Wiley & Sons, 1984.
- **Holman, J. P.,** Experimental Methods for Engineers, fifth Edition, McGraw-Hill book company, 1989.
- **Goldstein, R. J. (Ed.),** Fluid Mechanics Measurements, 2nd Ed., Taylor & Francis, Washington DC, 1996
- **Miller, R.W.,** Flow measurement engineering handbook, McGraw-Hill book company, 1983.
- **Tropea, C.,** Measuring techniques in experimental fluid mechanics, LSTM, Univ. Erlangen-Nuernberg, Erlangen, Germany, 1991.

References (II)

- **Doebelin, E.O.,** Measurement Systems, application and design, 4th Ed., McGraw-Hill book company, 1990.
- **Hinze, J.O.,** Turbulence, second edition, McGraw-Hill Book company, 1975.
- **Bradshaw, P.,** An Introduction to Turbulence and its Measurement, Pergamon Press, Oxford, 1971.
- **Schlichting, H.,** Boundary layer Theory, 7th edition, McGraw Hill Book Co., New York, 1979
- **Bendat, J.S., and Piersol, A. G.,** Random data: Analysis and Measurement Procedures, John Wiley & Sons, Inc, New York, 1971
- **王安邦等十六人合輯,** 雷射熱流量測基礎訓練課程講義, NTU-IAM, Taipei, June 30 – July 11, 1997
- **Conference Proceedings and Journal Papers**
  - (Proceedings of Applications of Laser Techniques to Fluid Mechanics, Proceedings of the International Symposium on Flow visualization, …..)

Topics of Term-Project

- 蔡俊雄: Mask optical optimization for metling-laser application
- 鄭聿: On the drop coalesce mechanism
- 邱鴻年: Design & development of a novel micro-reactor system
- 鄭珮妤: Development of medical contact lens & its measurement
- 趙士懿 : Development of medical contact lens & its measurement