CBE 30357
10/12/17

TOPICS

1) REVIEW: FLOW IN RECTANGULAR CHANNEL

ELLIPTIC PDE: SOLUTION BY SEPARATION OF VARIABLES.

- YOU SHOULD BE ABLE TO USE RESULT...

2) REVIEW "HYDRAULIC DIAMETER"

- NON-CIRCULAR CROSS-SECTION

- ALLOWS EXTENDING WHAT YOU ALREADY KNOW

3) EQUATIONS THAT DESCRIBE:

UNIFORM FLOW PAST A STATIONARY SPHERE

4) ANALYSIS OF NAVIER-STOKES EQUATIONS BY "DIMENSIONAL ANALYSIS"

5) FALL BREAK 🙂

RECTANGULAR CHANNEL
CROSS SECTION : h × w

x direction

$$\rho\left(\cancel{\frac{\partial v_x}{\partial t}} + \cancel{v_x\frac{\partial v_x}{\partial x}} + \cancel{v_y}\frac{\partial v_x}{\partial y} + \cancel{v_z}\frac{\partial v_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left[\cancel{\frac{\partial^2 v_x}{\partial x^2}} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right] + \cancel{\rho g_x} \tag{3.3.26a}$$

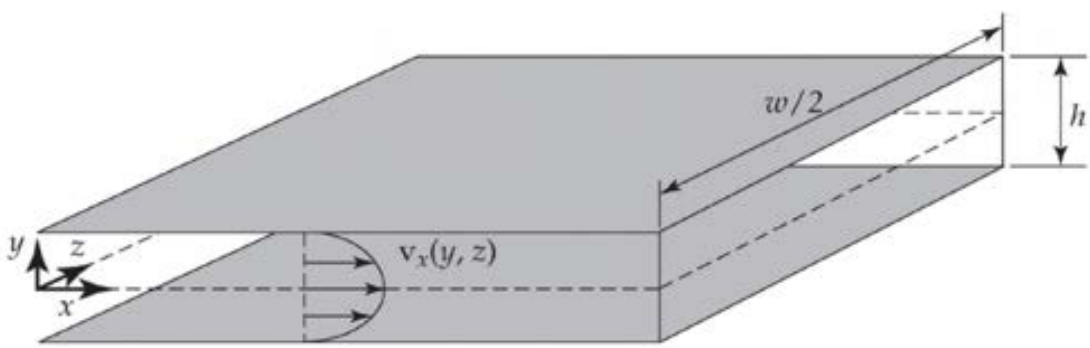
y direction

$$\rho\left(\cancel{\frac{\partial v_y}{\partial t}} + \cancel{v_x\frac{\partial v_y}{\partial x}} + \cancel{v_y\frac{\partial v_y}{\partial y}} + \cancel{v_z\frac{\partial v_y}{\partial z}}\right) = \cancel{-\frac{\partial p}{\partial y}} + \mu\left[\cancel{\frac{\partial^2 v_y}{\partial x^2}} + \cancel{\frac{\partial^2 v_y}{\partial y^2}} + \cancel{\frac{\partial^2 v_y}{\partial z^2}}\right] + \cancel{\rho g_y} \tag{3.3.26b}$$

z direction

$$\rho\left(\cancel{\frac{\partial v_z}{\partial t}} + \cancel{v_x\frac{\partial v_z}{\partial x}} + \cancel{v_y\frac{\partial v_z}{\partial y}} + \cancel{v_z\frac{\partial v_z}{\partial z}}\right) = \cancel{-\frac{\partial p}{\partial z}} + \mu\left[\cancel{\frac{\partial^2 v_z}{\partial x^2}} + \cancel{\frac{\partial^2 v_z}{\partial y^2}} + \cancel{\frac{\partial^2 v_z}{\partial z^2}}\right] + \cancel{\rho g_z} \tag{3.3.26c}$$

Figure 3.7 Flow in a rectangular channel of height *h* and width *w*. The section is through the plane $z = 0$.



PEARSON
Transport Phenomena in Biological Systems, Second Edition
George A. Truskey, Fan Yuan, and David F. Katz

$$0 = -\frac{\partial P}{\partial x} + \mu\left(\frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right)$$

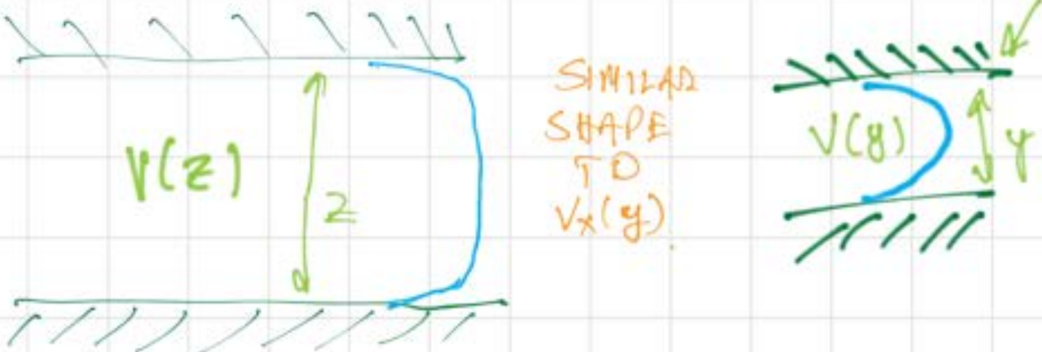
POISSON'S EQ

SOLVE BY SEPARATION OF VARIABLES: PP 138-139 TEXT

EIGENVALUE PROBLEM

and the solution for the velocity field is

$$v_x(y, z) = \frac{\Delta p h^2}{8\mu L}\left(1 - \frac{4y^2}{h^2}\right) - \frac{\Delta p h^2}{8\mu L}\sum_{n=0}^{\infty}\frac{32(-1)^n \cosh\big((2n+1)\pi z/h\big)\cos\big((2n+1)\pi y/h\big)}{(2n+1)^3\pi^3\cosh\big((2n+1)\pi w/2h\big)}.$$



BOTTOM WALL SHEAR STRESS:

$$\tau_{yx} = \frac{\mu}{W}\int_{-W/2}^{W/2} \left.\frac{\partial v_x}{\partial y}\right|_{y=-h/2} dz$$

$$= \frac{\Delta P h}{2L}\left[1 - 16\,\frac{h}{W}\sum_{n=0}^{\infty}\frac{(-1)^n \tanh\left((2n+1)\pi \frac{W}{2h}\right)}{(2n+1)^3\,\pi^3}\right]$$

ASPECT RATIO

$$\tau_{yx} \cong \left(\frac{-\partial P}{\partial x}\right) h\left(\frac{1}{2} - .25\,\varepsilon\right)$$

$$\varepsilon \equiv \frac{h}{W}$$

BOTTOM WALL, DOES NOT INCLUDE SIDES

HYDRAULIC DIAMETER

USE d_H FOR "DIAMETER"
IN STANDARD CORRELATIONS

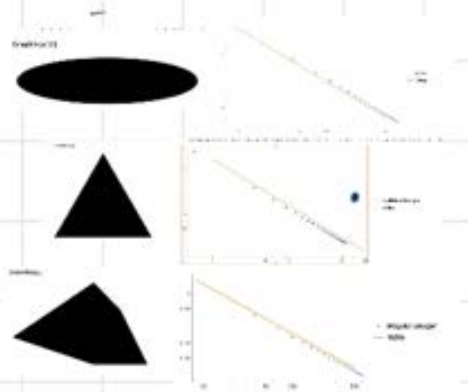
$$d_H = \frac{4\ \text{AREA}}{\text{PERIMETER}}$$

$$Re = \frac{\rho\, d_H V}{\mu} \qquad f = \frac{\Delta P\, d_H}{2 L \rho V^2}$$

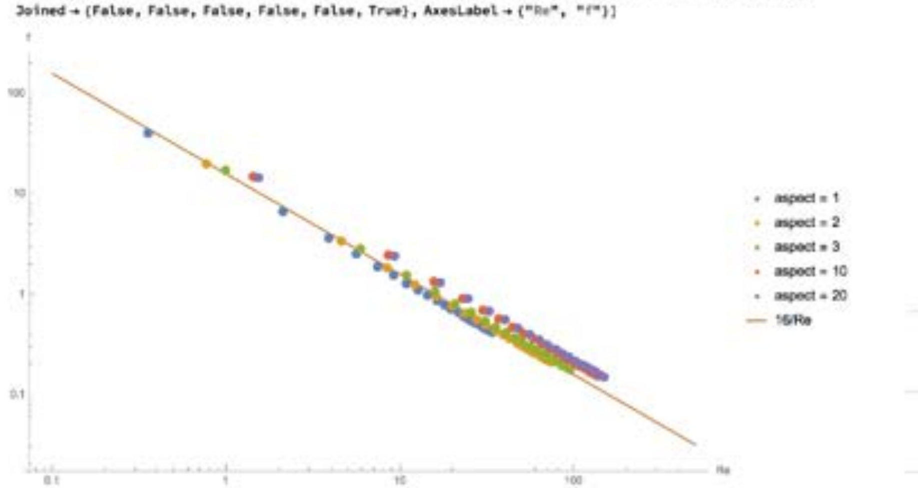
$$f = \frac{16}{Re}, \quad f = 0.079\, Re^{-.25}$$

LAMINAR FLOW: RECTANGULAR CROSS-SECTION

THIS WORKS WELL



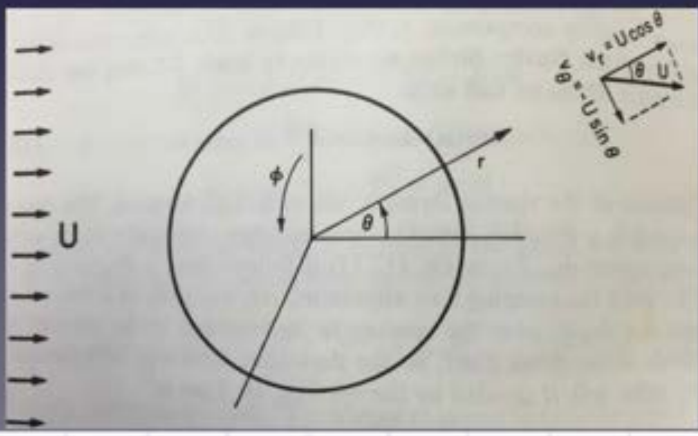
```
ListLogLogPlot[{ff1, ff2, ff3, ff10, ff20, ff16Re},
 PlotLegends → {"aspect = 1", "aspect = 2", "aspect = 3", "aspect = 10", "aspect = 20", "16/Re"},
 Joined → {False, False, False, False, False, True}, AxesLabel → {"Re", "f"}]
```



You can see that for aspect ratio = 1, 2, 3... 5, the hydraulic diameter works well.

Simple flow of interest

- Flow of liquid past a stationary sphere (which is the same as single particle moving (perhaps by gravity) through an otherwise quiescent liquid (or gas).
- Here is drawing from Denn's book:



Non-Zero Terms

TABLE 3.4

(*Continued*)

Spherical coordinates

r direction

$$\rho\left[\cancel{\frac{\partial v_r}{\partial t}} + \boxed{v_r\frac{\partial v_r}{\partial r}} + \boxed{\frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}} + \cancel{\frac{v_\phi}{r\sin\theta}\frac{\partial v_r}{\partial \phi}} - \boxed{\frac{v_\theta^2 + \cancel{v_\phi^2}}{r}}\right] = \boxed{-\frac{\partial p}{\partial r}} + \cancel{\rho g_r}$$
$$+ \mu\left[\boxed{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_r}{\partial r}\right)} + \boxed{\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial v_r}{\partial \theta}\right)} + \cancel{\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_r}{\partial \phi^2}} \boxed{- 2\frac{v_r}{r^2} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta} - \frac{2}{r^2}v_\theta\cot\theta} - \cancel{\frac{2}{r^2\sin\theta}\frac{\partial v_\phi}{\partial \phi}}\right]$$

L. H. S.

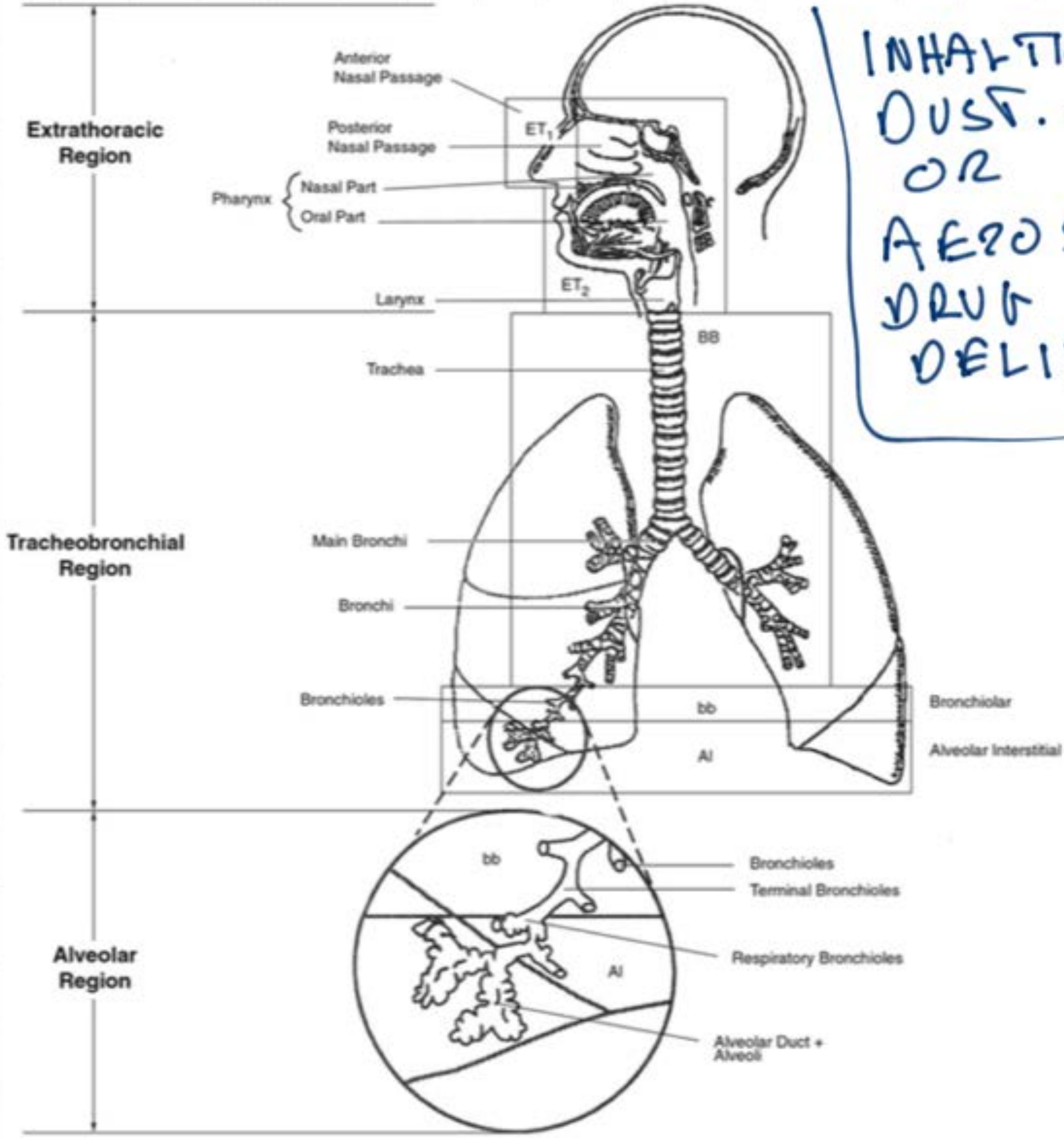
$\vec{v}\cdot\vec{\nabla}\vec{v} \neq 0$

θ direction

$$\rho\left(\cancel{\frac{\partial v_\theta}{\partial t}} + \boxed{v_r\frac{\partial v_\theta}{\partial r}} + \boxed{\frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta}} + \cancel{\frac{v_\phi}{r\sin\theta}\frac{\partial v_\theta}{\partial \phi}} + \boxed{\frac{v_\theta v_r}{r}} - \cancel{\frac{v_\phi^2\cot\theta}{r}}\right) = \boxed{-\frac{1}{r}\frac{\partial p}{\partial \theta}} + \mu\left[\boxed{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\theta}{\partial r}\right)}\right.$$
$$\left.+ \boxed{\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial v_\theta}{\partial \theta}\right)} + \cancel{\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\theta}{\partial \phi^2}} + \boxed{\frac{2}{r^2}\frac{\partial v_r}{\partial \theta} - \frac{v_\theta}{r^2\sin^2\theta}} - \cancel{\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\phi}{\partial \phi}}\right] + \cancel{\rho g_\theta}$$

ϕ direction

$$\rho\left(\cancel{\frac{\partial v_\phi}{\partial t}} + \cancel{v_r\frac{\partial v_\phi}{\partial r}} + \cancel{\frac{v_\theta}{r}\frac{\partial v_\phi}{\partial \theta}} + \cancel{\frac{v_\phi}{r\sin\theta}\frac{\partial v_\phi}{\partial \phi}} + \cancel{\frac{v_\phi v_r}{r}} + \cancel{\frac{v_\theta v_\phi}{r}\cot\theta}\right) = \boxed{-\frac{1}{r\sin\theta}\frac{\partial p}{\partial \phi}} + \mu\left[\cancel{\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v_\phi}{\partial r}\right)}\right.$$
$$\left.+ \cancel{\frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial v_\phi}{\partial \theta}\right)} + \cancel{\frac{1}{r^2\sin^2\theta}\frac{\partial^2 v_\phi}{\partial \phi^2}} + \cancel{\frac{2}{r^2\sin\theta}\frac{\partial v_r}{\partial \phi}} - \cancel{\frac{v_\phi}{r^2\sin^2\theta}} + \cancel{\frac{2\cos\theta}{r^2\sin^2\theta}\frac{\partial v_\theta}{\partial \phi}}\right] + \cancel{\rho g_\phi}$$



INHALATION OF DUST... OR AEROSOL DRUG DELIVERY

TORTUOUS PATH, PARTICLES STICK TO WALL: CLEARED BY CILIA.
LONG PATH: ONLY LAST ~5 BRANCHES ABSORB
OR, COULD BREATH BACK OUT.

AEROSOL DRUG DELIVERY

Review Article

The Transport and Deposition of Nanoparticles in Respiratory System by Inhalation

Huiting Qiao,[1,2] Wenyong Liu,[1] Hongyu Gu,[1] Daifa Wang,[1] and Yu Wang[1]

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The inhaled nanoparticles have attracted more and more attention, since they are more easily to enter the deep part of respiratory system. Some nanoparticles were reported to cause pulmonary inflammation. The toxicity of nanoparticles depends not only on its

topical respiratory treatment it is best to use particles with an MMAD between 0.5 and 5 μm. This is what is known as the breathable fraction of an aerosol.[6]

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ELSEVIER

Review

Pulmonary drug delivery by powder aerosols

Michael Yifei Yang, John Gar Yan Chan, Hak-Kim Chan *

Advanced Drug Delivery Group, Faculty of Pharmacy (A15), University of Sydney, Sydney, NSW 2006, Australia

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ABSTRACT

The efficacy of pharmaceutical aerosols relates to its deposition in the clinically relevant regions of the lungs, which can be assessed by *in vivo* lung deposition studies. Dry powder formulations are popular as devices are por-

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ELSEVIER

Review

Influence of particle size on regional lung deposition – What evidence is there?

Thiago C. Carvalho[a], Jay I. Peters[b], Robert O. Williams III[a,*]

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ABST

The unders
of inhalati

Deposition of Inhaled Particles in the Human Respiratory Tract and Consequences for Regional Targeting in Respiratory Drug Delivery

Joachim Heyder

GSF–National Research Center for Environment and Health, Institute for Inhalation Biology, Neuherberg/Munich, Germany

Particle behavior in the human respiratory tract is well understood and can be used to (*1*) estimate particle deposition in all regions

(decreasing respiratory rate). Total diffusional deposition therefore decreases with increasing particle size up to about 1 μm

IN GENERAL, WE CAN'T GET AN ANALYTICAL SOLUTION TO A NONLINEAR P.D.E.

PERHAPS, SOME SIMPLIFICATIONS COULD BE JUSTIFIED....

HOW CAN THIS BE DONE?

1) WE NEED A PROCEDURE THAT ESTIMATES (BRACKETS) THE MAGNITUDE OF INDIVIDUAL TERMS

2) FROM THIS, WE CAN GO A STEP FURTHER, NONDIMENSIONALIZE EQ.

3) WHEN THIS IS DONE, A PARAMETER "APPEARS" REYNOLDS NUMBER.

4) IN THE LIMIT $Re \to 0$ L.H.S. TERMS CAN BE NEGLECTED....

WE CAN SOLVE SOME PROBLEMS

HOW TO ESTIMATE (RELATIVE) SIZE OF THESE TERMS

$$\rho v_r \frac{\partial v_r}{\partial r} \simeq \rho v_r \frac{\Delta v_r}{\Delta r}$$

$$v_r \sim U_0$$
$$\Delta v_r \sim U_0$$
$$\Delta r \sim \underline{2,3\ldots}\ R$$

ABOUT THIS BIG

THUS

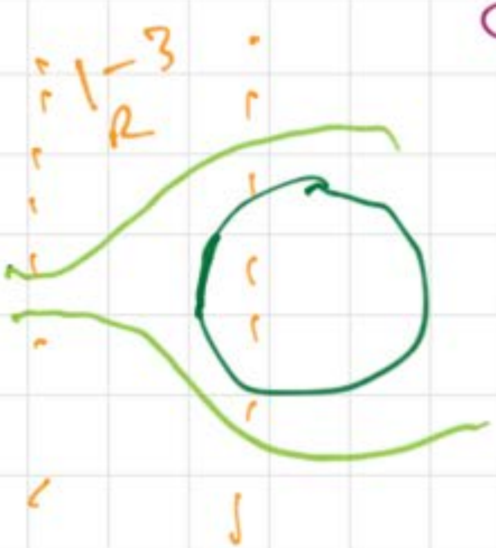
$$\rho v_r \frac{\partial v_r}{\partial r} \simeq \underline{\#}\rho \frac{U_0^2}{R}$$

HOW ABOUT VISCOUS TERM ?

$$\mu \frac{1}{r^2}\frac{\partial}{\partial r} r^2 \frac{\partial v_r}{\partial r}$$

ONE PIECE

$$\mu \frac{\partial^2 v_r}{\partial r^2} = \mu \frac{\partial}{\partial r}\left(\frac{\partial v_r}{\partial r}\right)$$



$$\cong \mu \frac{1}{\Delta r}\left(\frac{\Delta v}{\Delta r}\Big|_1 - \frac{\Delta v}{\Delta r}\Big|_2\right)$$

$$\simeq \frac{\mu}{R}\left(\frac{U_0}{R}\right)$$

$$= \mu \frac{U_0}{R^2}$$

TAKE RATIO

$$\frac{\rho U_0^2/R}{\mu U_0/R^2} = \frac{\rho U_0 R}{\mu} = Re$$

WE SURMISE THAT IF

$Re \ll 1$, WE CAN

NEGLECT INERTIA

TERMS RELATIVE TO

VISCOUS TERMS!!

IF SO: EQUATIONS WILL BE LINEAR.

WE CAN FORMALIZE THIS

BY NONDIMENSIONALIZING

OUR EQUATIONS

EACH TERM IS "COMPARED" TO SCALES OF PROBLEM.

LENGTH SCALE: R

VELOCITY SCALE: U_0

TIME SCALE: R/U_0

DEFINE:

$$V_r^* = \frac{V_r}{U_0} \qquad V_\theta^* = \frac{V_\theta}{U_0}$$

$$r^* = \frac{r}{R} \qquad r = r^* R$$

SUBSTITUTE DEPENDENT VARIABLES

USE CHAIN RULE FOR DERIVATIVES

$$\frac{\partial}{\partial r} = \frac{\partial}{\partial r^*}\frac{\partial r^*}{\partial r} = \Big(\underbrace{\frac{\partial r^*}{\partial r}}_{1/R}\Big)\frac{\partial}{\partial r^*}$$

$$\frac{\partial v_r}{\partial r} = \frac{\partial r^*}{\partial r}\frac{\partial}{\partial r^*}\left(U_0 v_r^*\right)$$

$$= \frac{U_0}{R}\frac{\partial v_r^*}{\partial r^*}$$

$$\frac{\partial^2 v_r}{\partial r^2} = \left(\frac{\partial r^*}{\partial r}\right)^2 U \frac{\partial^2 v_r^*}{\partial r^{*2}}$$

$$= \frac{U}{R^2}\frac{\partial^2 v_r^*}{\partial r^{*2}}$$

WHEN YOU GET DONE

$$v_r^* \frac{\partial v_r^*}{\partial r^*} = O(1)$$

$$\frac{\partial^2 v_r^*}{\partial r^{*2}} = O(1)$$

MOST IMORTANT POINT!!

WE NEED p^*

$$P_c \equiv \frac{\mu U_0}{R} \quad \therefore \; p^* = \frac{p}{\mu U_0/R}$$

FOR ALL TERMS ...

$$Re\left(\vec{V}^* \cdot \vec{\nabla}^* \vec{V}^*\right) = -\vec{\nabla}^* p^* + \nabla^{*2} \vec{V}^*$$

$$\mathcal{O}(1) \qquad \mathcal{O}(1) \qquad \mathcal{O}(1)$$

THEN IF $Re \to 0$ WE GET

$$\boxed{\vec{\nabla}^* p^* = \nabla^{*2} \vec{V}^*}$$

STOKES EQUATION

LINEAR PDE

MANY SOLUTIONS ARE KNOWN

... YES, BUT ARE THESE USEFUL??

FOR PEARL IN 1960'S COMMERCIAL

$$Re = \frac{D v \rho_f}{\mu_f} = \frac{(1.5\,cm)(.5\,cm/s)(1\,g/cm^3)}{4\,g/cm\text{-}s}$$

$$Re \simeq .2$$

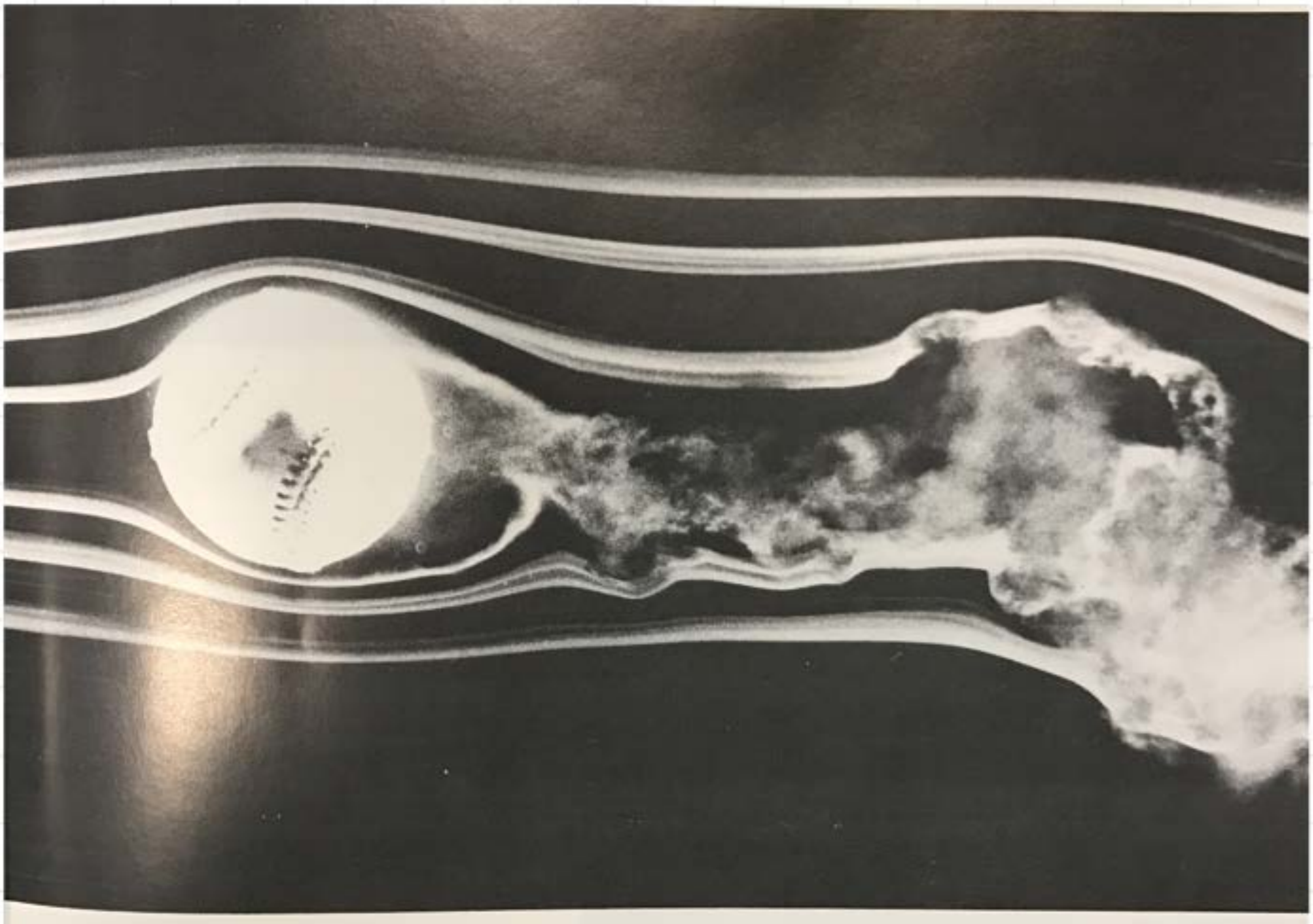
FOR 10 μm PARTICLE IN AIR

$$Re = \frac{(10^{-3}\,cm)(.1\,cm/s)\left(\frac{1}{890}\,g/cm^3\right)}{.00018\,g/cm\text{-}s}$$

$$= 6 \times 10^{-3}$$

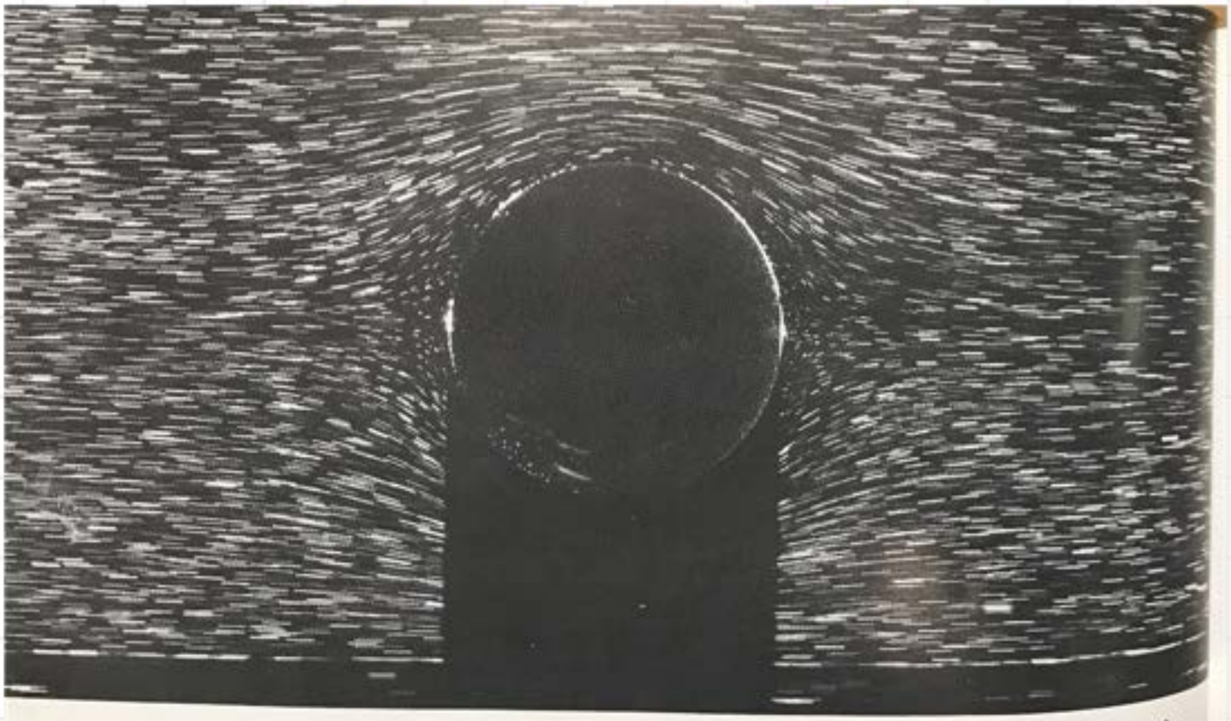
WHAT WOULD FLOW PAST A SPHERE AT LOW Re LOOK LIKE?

NOT THIS:



66. Spinning baseball. The late F. N. M. Brown devoted many years to developing and using smoke visualization in wind tunnels at the University of Notre Dame. Here the flow speed is about 77 ft/sec and the ball is rotated at 630 rpm. This unpublished photograph is similar to several in Brown 1971. *Photograph courtesy of T. J. Mueller*

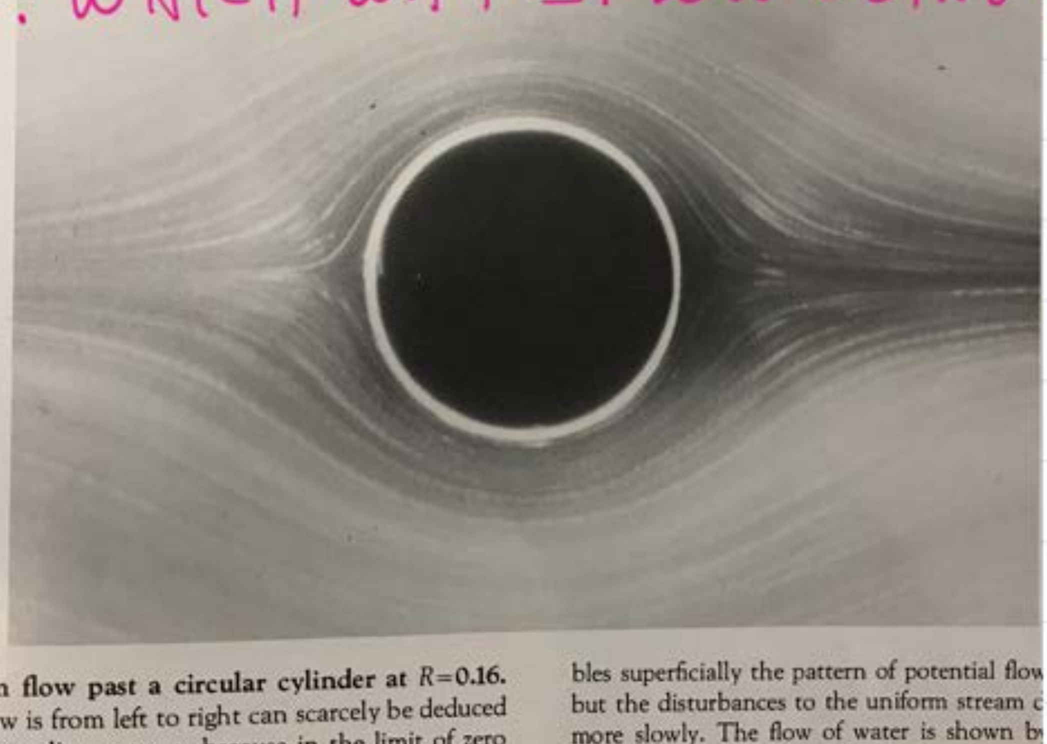
LOW Re FLOWS...



NO WAKE

8. **Sphere moving through a tube at $R=0.10$, relative motion.** A free sphere is falling steadily down the axis of a tube of twice its diameter filled with glycerine. The camera is moved with the speed of the sphere to show the flow relative to it. The photograph has been rotated to show flow from left to right. Tiny magnesium cuttings are illuminated by a thin sheet of light, which casts a shadow of the sphere. *Coutanceau 1968*

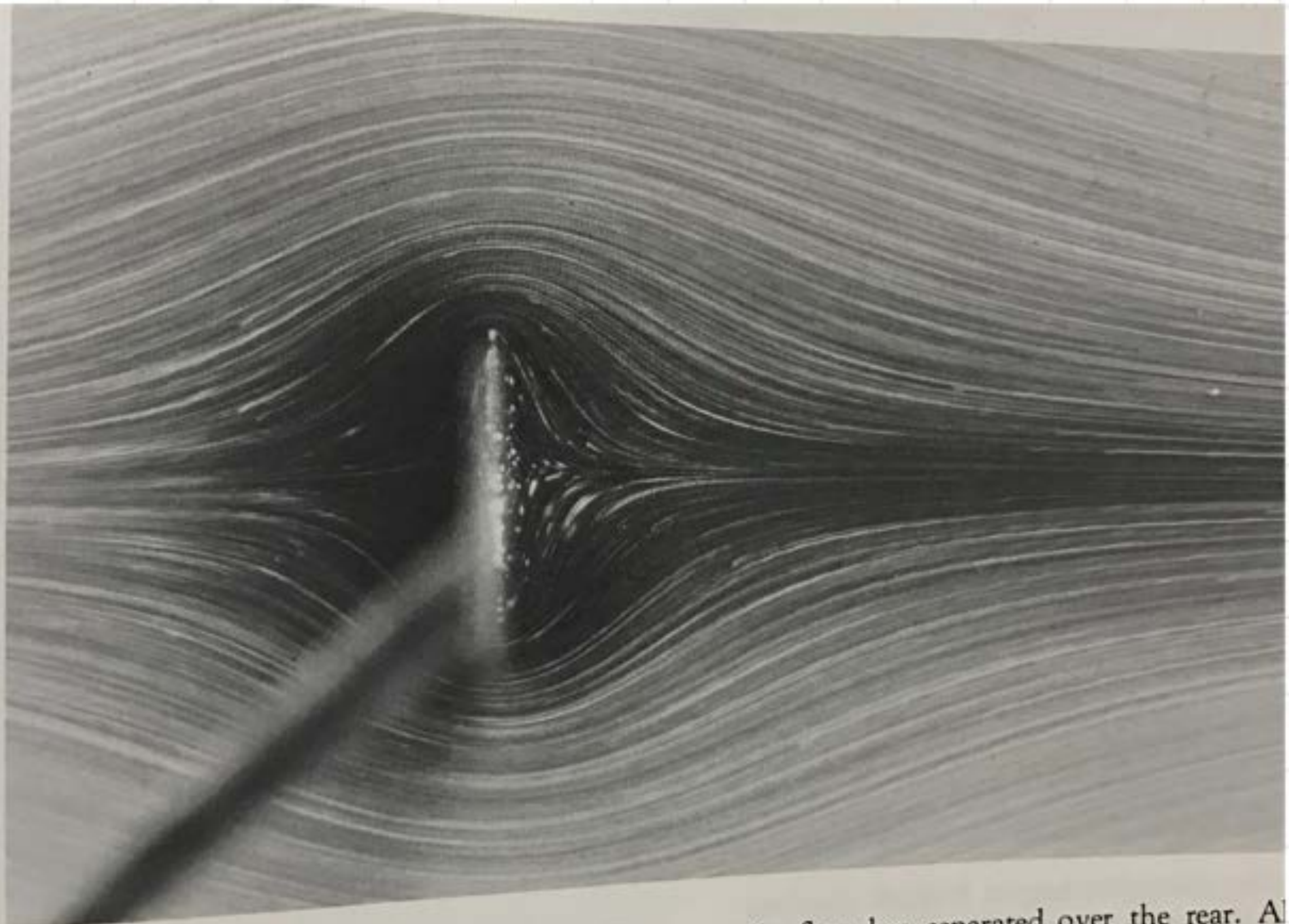
SYMMETRIC: WHICH WAY IS FLOW GOING?



. **Uniform flow past a circular cylinder at $R=0.16$.** hat the flow is from left to right can scarcely be deduced om the streamline pattern, because in the limit of zero eynolds number the flow past a solid body is reversible, nd hence symmetric about a symmetric shape. It resembles superficially the pattern of potential flow but the disturbances to the uniform stream c more slowly. The flow of water is shown b dust. *Photograph by Sadatoshi Taneda*

LOW Re:

EVEN A FLAT PLATE HAS NO WAKE



Jniform flow normal to a plate at R=0.334. The ımline pattern is still almost symmetric fore-and-aft at higher Reynolds number. It is possible, however, that the flow has separated over the rear. Al shows the flow of glycerine. *Taneda 1968*

BESIDES OLD TV COMMERCIALS WHERE DO THESE FLOWS OCCUR?

1) PROCESS FLOWS OF SUSPENSIONS
   a) FOODS.
   b) CONSUMER PRODUCTS
   c) COMPOSITE MOLDING
   d) SOLID-LIQUID MIXING
   e) SOLIDS TRANSPORT
   f) FLUIDIZED BED REACTORS
2) MEDICAL: INHALERS FOR DRUG DELIVERY
3) ENVIRONMENT: AEROSOLS, SEDIMENT TRANSPORT

TAKE SPECIFIC EXAMPLE OF "INHALERS"

PROCESS INVOLVES EITHER

NEBULIZING A LIQUID INTO SMALL DROPS

OR DISPERSING SMALL PARTICLES INTO A CARRIER GAS

IN EITHER CASE, SOUNDS LIKE A GREAT IDEA!!

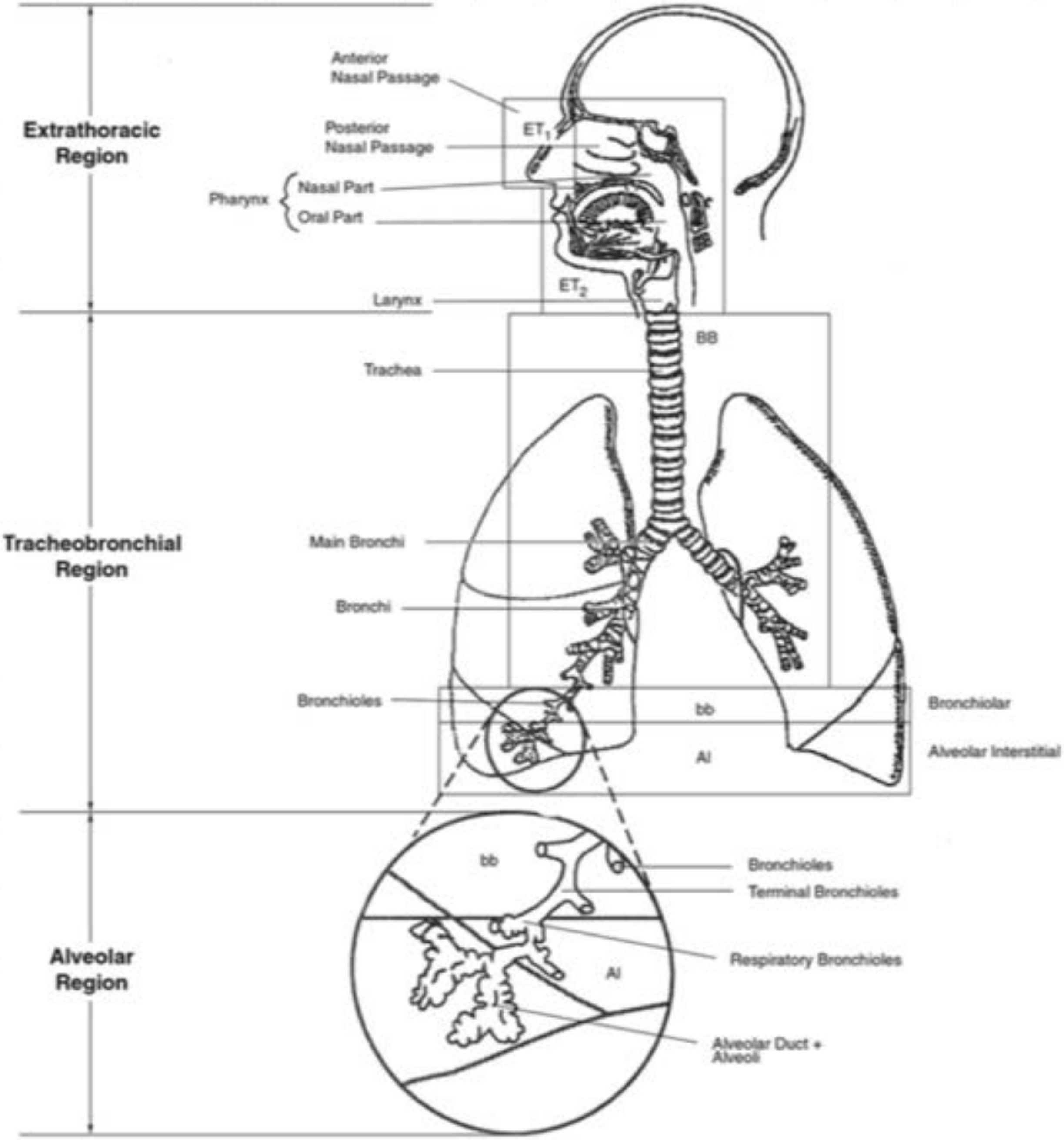
A) YOU DIRECTLY APPLY ANTI-INFLAMMATORY AGENT TO LUNG TISSUE.

B) QUICK PATH TO BLOOD STREAM FOR PHARMACEUTICALS THAT CAN'T EASILY BE DELIVERED BY PILLS.

THERE ARE SOME PROBLEMS

1) HUMANS HAVE HAD TO DEAL WITH AIRBORNE SOLID PARTICLES... ALWAYS

YOU HAVE DEFENSES



TORTUOUS PATH, PARTICLES STICK TO WALL: CLEARED BY CILIA.

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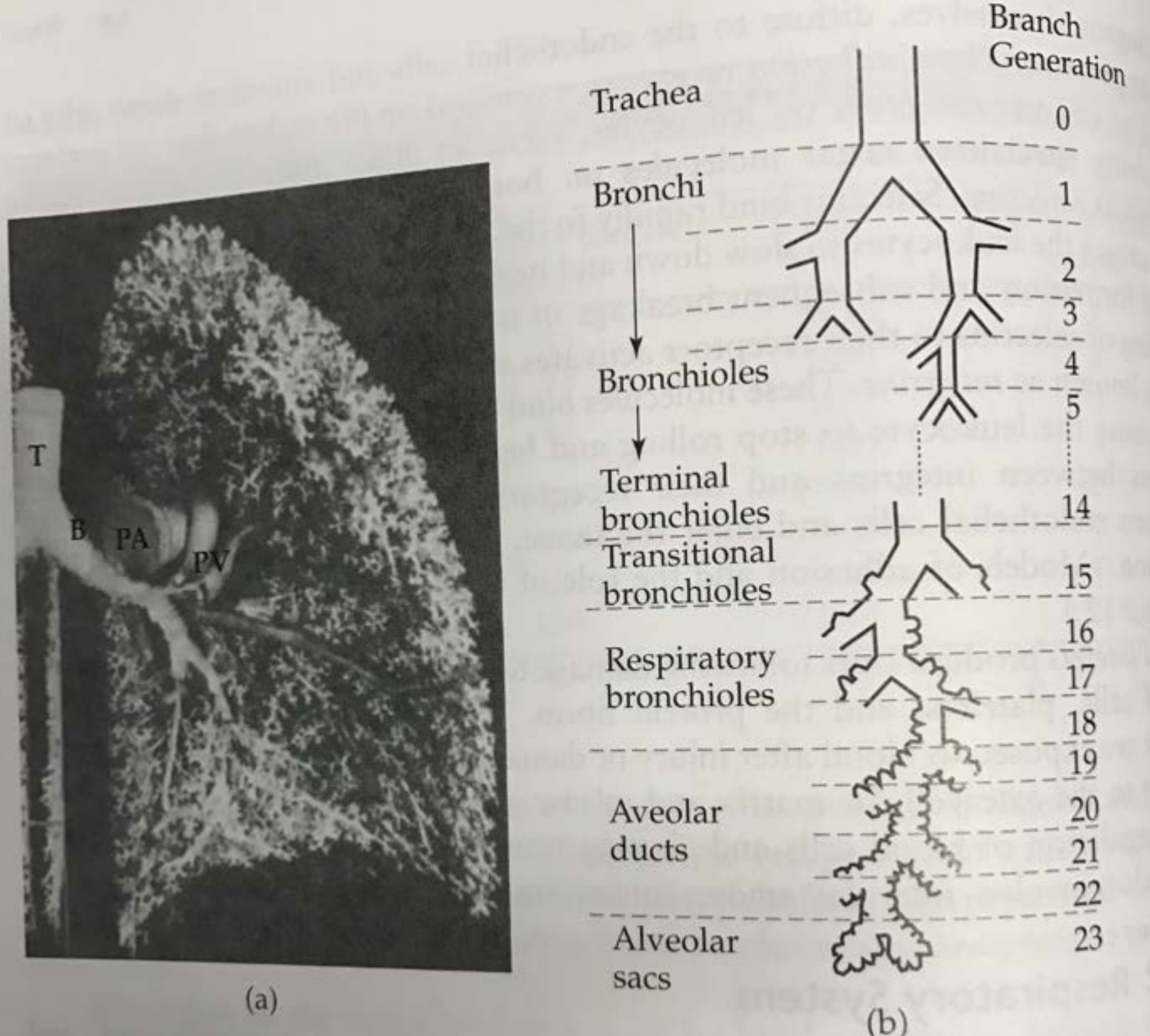

FIGURE 1.13 (a) Cast of a human lung, showing the trachea (T), one bronchus (B), the pulmonary artery (PA), and the pulmonary vein (PV). (b) Schematic of the organization of the airways in the human lung. (From Ref. [13], used with permission.)

TABLE 1.14

Morphometric Data for the Bronchi of a Human Lung		
Order[a]	Mean diameter (mm)	Mean length (mm)
0	18.0	120.0
1	12.2	47.6
2	8.3	19.0
3	5.6	7.6
4	4.5	12.7
5	3.5	10.7
6	2.8	9.0
7	2.3	7.6
8	1.86	6.4
9	1.54	5.4
10	1.3	4.6
11	1.09	3.9
12	0.95	3.3
13	0.82	2.7
14	0.74	2.3
15	0.66	2.0
16	0.6	1.65
17	0.54	1.41
18	0.5	1.17
19	0.47	0.99
20	0.45	0.83
21	0.43	0.7
22	0.41	0.59
23	0.41	0.5

Source: Adapted from Ref. [14].

[a]The trachea is called the airway of order 1, and the alveoli are the airways of order 23

WIDELY USED, BUT SUBJECT OF CONTINUOUS STUDY:

Review Article

The Transport and Deposition of Nanoparticles in Respiratory System by Inhalation

Huiting Qiao,[1,2] Wenyong Liu,[1] Hongyu Gu,[1] Daifa Wang,[1] and Yu Wang[1]

[1] *Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China*
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Particle behavior in the human respiratory tract is well understood and can be used to (1) estimate particle deposition in all regions

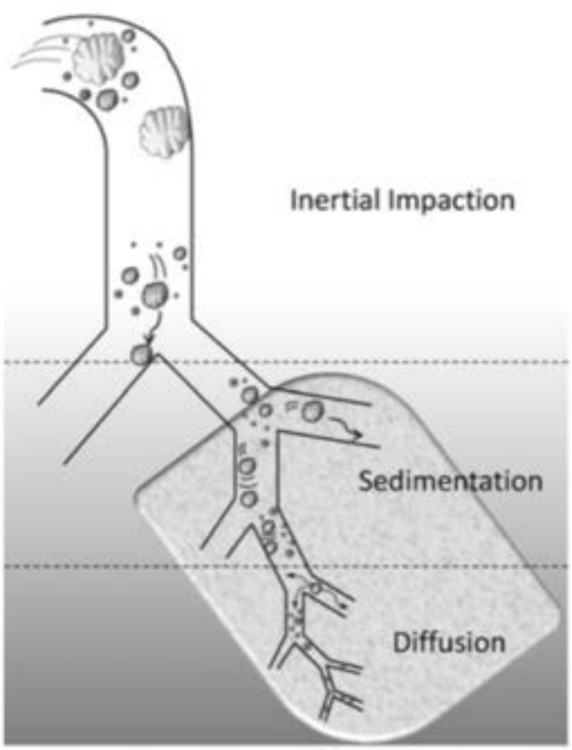
(decreasing respiratory rate). Total diffusional deposition therefore decreases with increasing particle size up to about 1 μm

SEEMS LIKE IT IS SAFE TO SAY THAT YOU ARE OPTIMIZED FOR THE TRADEOFFS OF EFFICIENT BREATHING VERSUS PROTECTION FROM PARTICLES

The respiratory tract is especially designed, both anatomically and functionally, so that air can reach the most distal areas of the lungs in the cleanest possible condition. Nasal hairs, nasal turbinates, vocal chords, the cilia of the bronchial epithelium, the sneeze and cough reflexes, etc., all contribute to this filtering process. And, on most occasions it is properly done. But human beings are full of paradoxes: an efficient system, designed to avoid certain

particles from penetrating into the lungs, is at the same time used to intentionally deposit drugs in the airways and even for these to reach the alveoli in the best possible condition. It is thus necessary to get around the defense systems by evading reflex arcs, mucus layers, ciliary movements, etc., so that, with the inspiratory flow, the molecules that can improve diseases are deposited in the lungs. A system that evolved over time in order to filter and clean the air should be dodged in order to deposit other substances that we deliberately want to reach the inside of the organism. Without a

PARTICLE CLEARING MECHANISMS



Inertial Impaction	Sedimentation	Diffusion
Directly related to d^2	Directly related to d^2	Inversely related to d
$Stk = \frac{\rho_p \cdot d^2 \cdot V}{18 \cdot \eta \cdot R}$	$V_{ts} = \frac{(\rho_p - \rho_a) \cdot d^2 \cdot g}{18 \cdot \eta}$	$Dif = \frac{k \cdot T}{3\pi \cdot \eta \cdot d}$

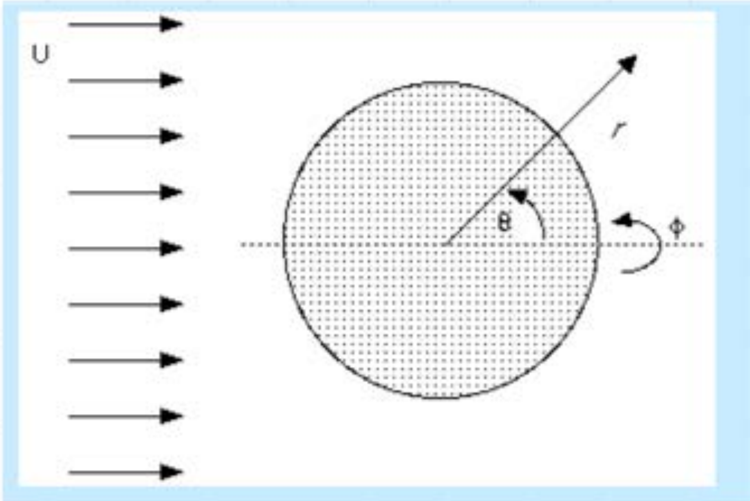
Aerodynamic Diameter: $d_{ae} = d \cdot \sqrt{\frac{\rho}{\rho_0}}$

Fig. 2. The influence of particle size on deposition. *d*: particle diameter; *Stk*: Stokes number; ρ_p: particle density; *V*: air velocity; η: air viscosity; *R*: airway radius; V_{ts}: terminal settling velocity; ρ_a: air density; *g*: gravitational acceleration; *Dif*: diffusion coefficient; *k*: Boltzmann's constant; *T*: absolute temperature; d_{ae}: aerodynamic diameter; ρ_0: unity density.

B, mass, *m*, and velocity, *v*, according to Eq. (1) (Gonda, 2004):

WHERE DO EQUATIONS COME FROM?

SOLUTION TO NAVIER-STOKES EQUATIONS FOR FLOW PAST A SPHERE: $Re \Rightarrow 0$



USE SPHERICAL COORDINATES

- CONTINUITY EQ.
- r-DIRECTION N.S. EQ
- θ-DIRECTION N.S. EQ

$\Big\}\ Re \to 0$

JUST THE R.H.S.'S

$V_r(r=R)=0 \quad V_\theta(r=R)=0$

$V_r(r\to\infty) = U\cos\theta$

$V_\theta(r\to\infty) = -U\sin\theta$

SOLUTION PROCEDURE

SEQUENTIALLY CONSIDER 3 PDE'S USING AN ASSUMED FORM OF SOLUTION

$$\left.\begin{aligned} U_r &\sim f(r)\cos\theta \\ U_\theta &\sim g(r)\sin\theta \end{aligned}\right\} \text{FROM B.C.'S}$$

CONTINUITY EQUATION ALLOWS EASY ISOLATION OF

$g(r)$

SUBS THIS TO ELIMINATE $g(r)$ IN U_r + U_θ EQ'S

TAKE CROSS-DERIVATITIVES AND SUBTRACT V_r + V_θ EQ TO ELIMINATE PRESSURE

SOLVE 4TH ORDER
EULER ODE.

FIT B.C.'S 👍

DRAG = $6\pi\mu R U$

WE GET: SETTLING VELOCITY

EINSTEIN USED THIS
TO CALCULATE DIFFUSIVITY
OF A PARTICLE

BOLTZMANN CONSTANT

$$D = \frac{KT}{6\pi\mu R}$$

PARTICLE DIFFUSIVITY

PARTICLE RADIUS