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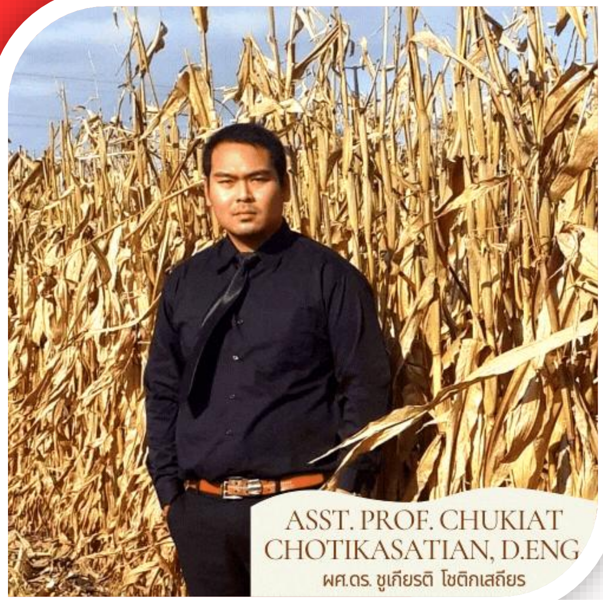
9673204
Drying and Storage



Course Description

Theory of drying, sun drying, principles of air flow, drying of agricultural products by heated air, moisture content determination, relationship of moisture and temperature, equilibrium moisture content, design of dryers, storage

Professional Interest Statement:

- Monitoring CO_2/O_2 concentrations to assess biological activity and reduce post-harvest losses
- Establishing verification criteria for unacceptable insect infestation levels
- Supporting fumigation and grain storage management decisions
- Developing agricultural product drying and intelligent drying systems

Assistant Professor Dr. Chukiat Chotikasatian
Office: ETB 101 - Industrial Education
Faculty of Science and Technology
Webpage: https://pws.npru.ac.th/chukiat/

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Lecture 3 – Flow Resistance Calculation and Fan Selection

Study Questions – Lecture 3

1. *Why is airflow resistance important in agricultural drying systems?*
2. *What factors contribute to pressure drop in grain beds and air ducts?*
3. *How can airflow resistance be calculated in drying systems?*
4. *How are fans selected based on airflow and pressure requirements?*

Lecture 3 – Flow Resistance Calculation and Fan Selection

Outline – Lecture 3

1. *Importance of Flow Resistance in Drying Systems*
2. *Airflow resistance in grains (Pressure Drop)*
3. *Friction in pipes and ducts*
4. *Fan types and classification*

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Why is Flow Resistance Important in Drying Systems?

- ✓ Flow resistance determines the required fan pressure and power
- ✓ High resistance increases energy consumption
- ✓ Low airflow reduces drying rate and uniformity
- ✓ Proper resistance control ensures efficient and stable drying
- ✓ Airflow through granular materials (grains) creates resistance (pressure drop)

What Causes Flow Resistance or Pressure Drop in a System?

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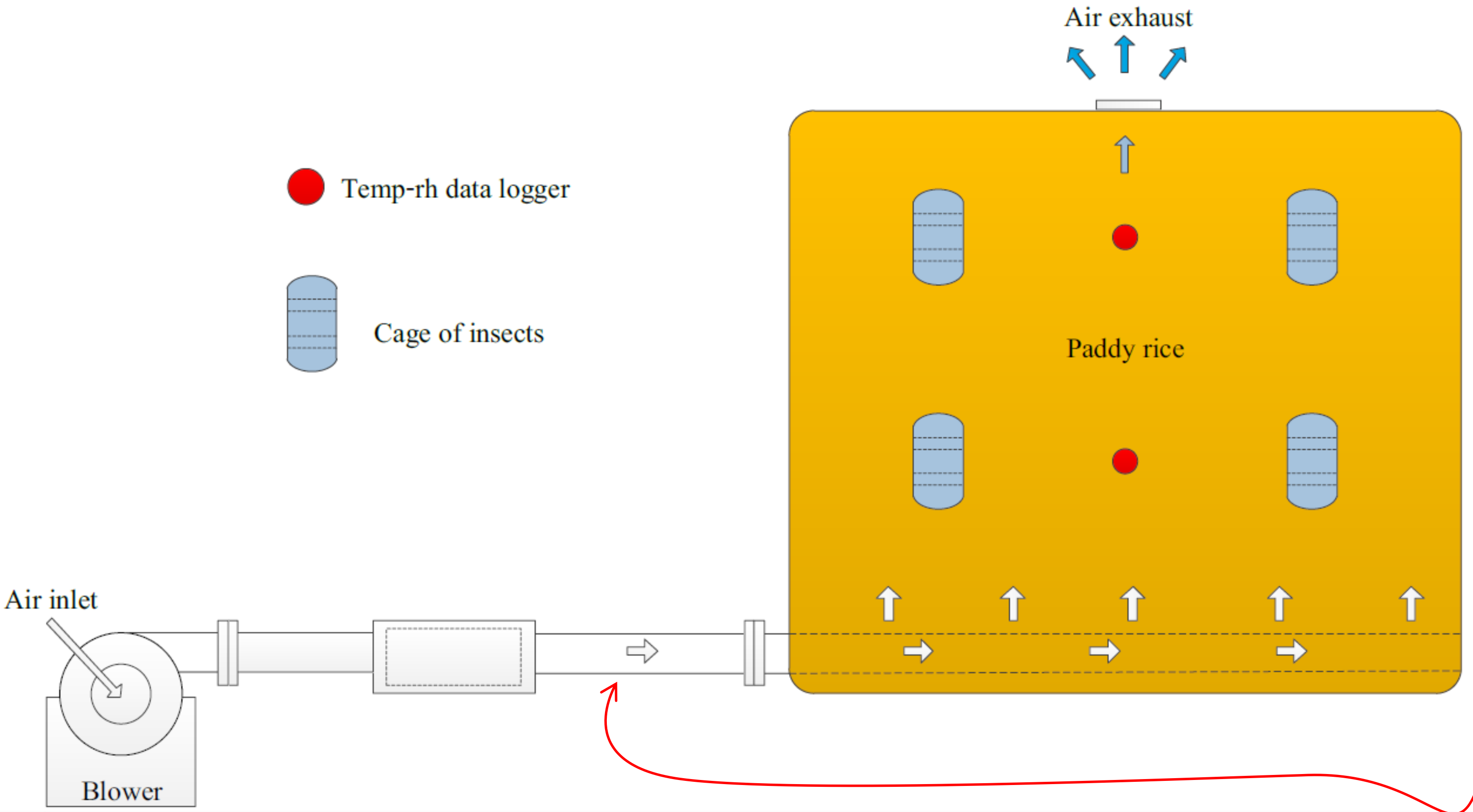

- Friction between the air and duct walls

What Causes Flow Resistance or Pressure Drop in a System?

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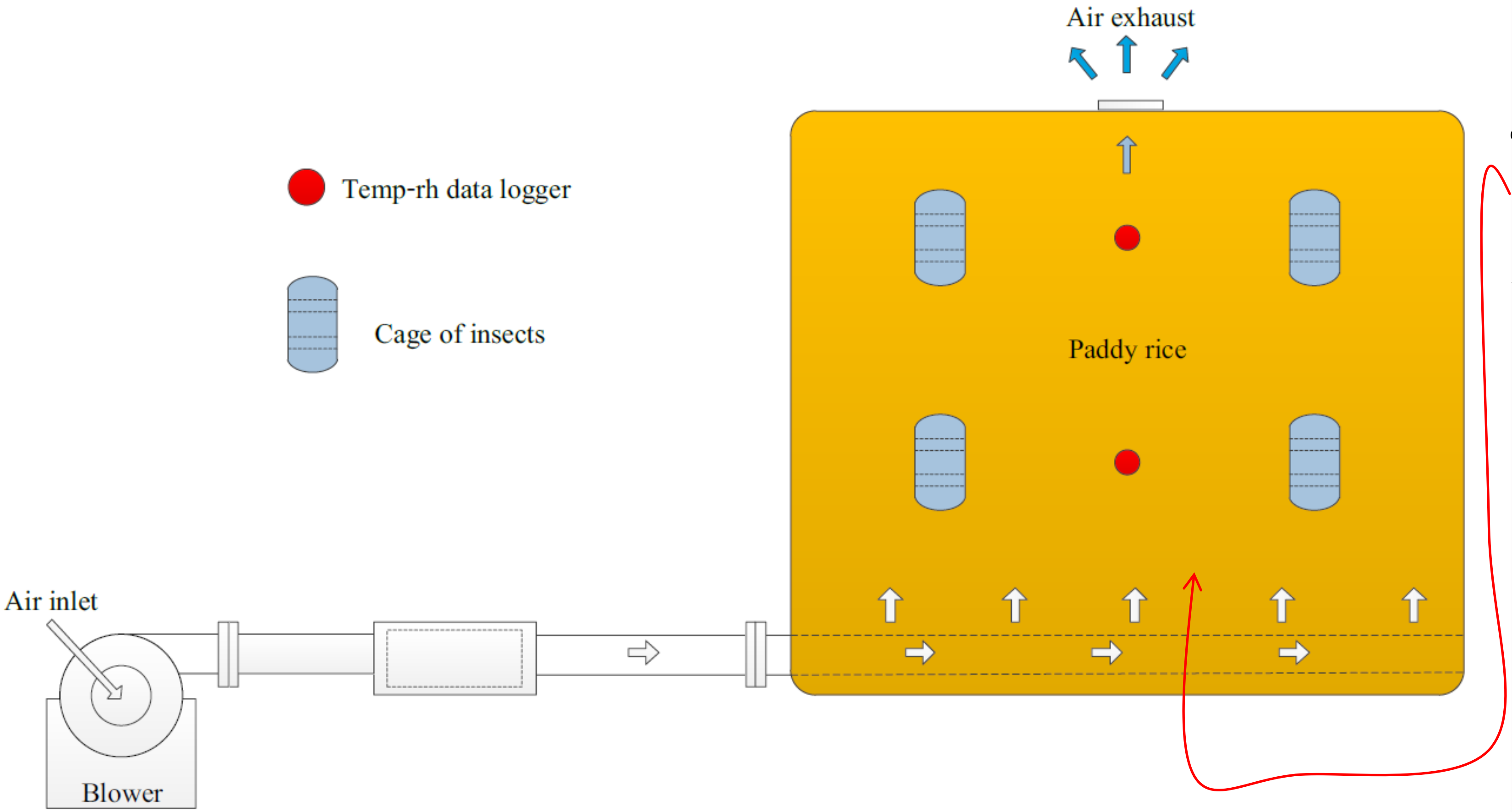
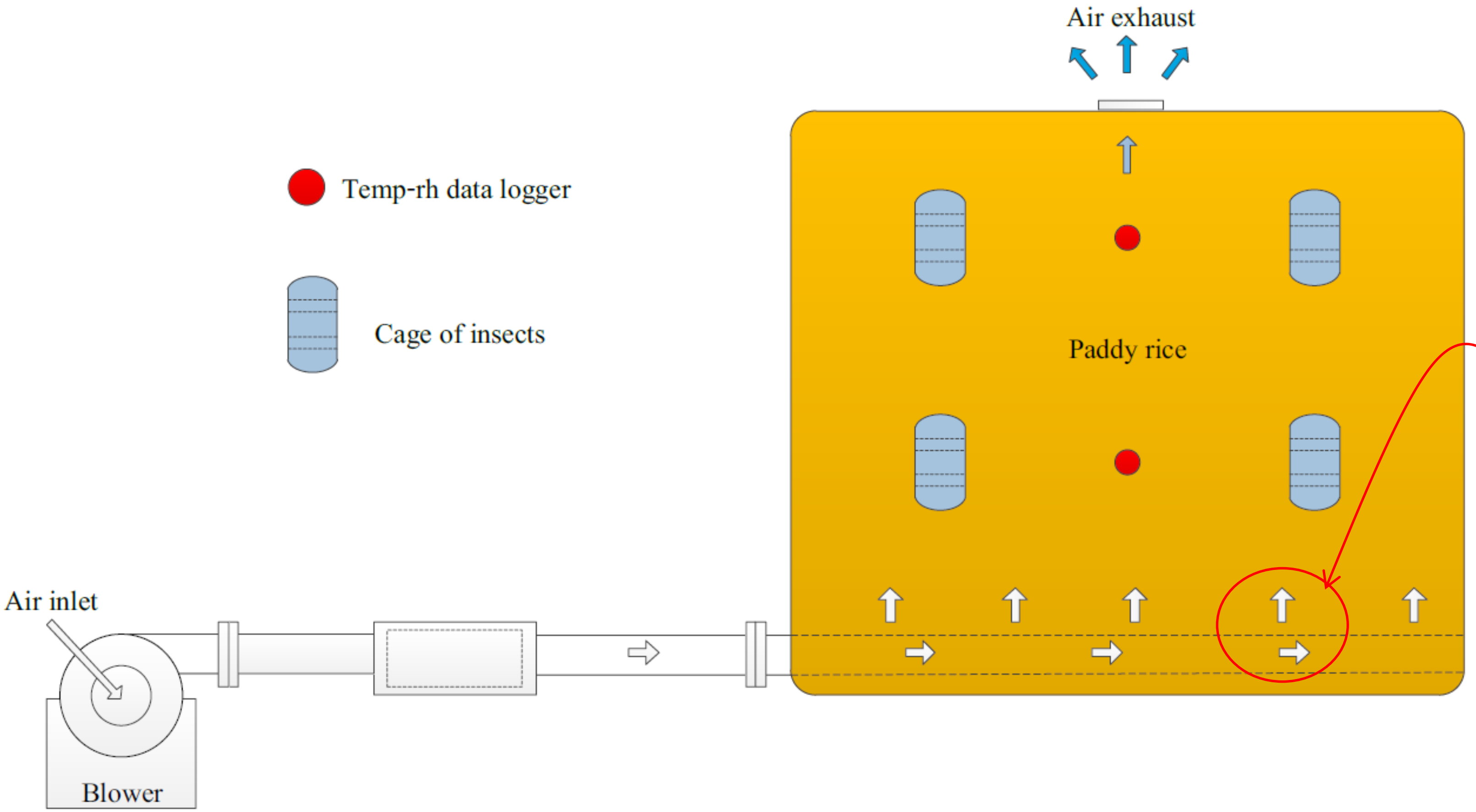


- Friction between the air and duct walls
- **Flow through porous materials**

What Causes Flow Resistance or Pressure Drop in a System?



- Friction between the air and duct walls
- Flow through porous materials
- **Changes in flow direction**

What Causes Flow Resistance or Pressure Drop in a System?

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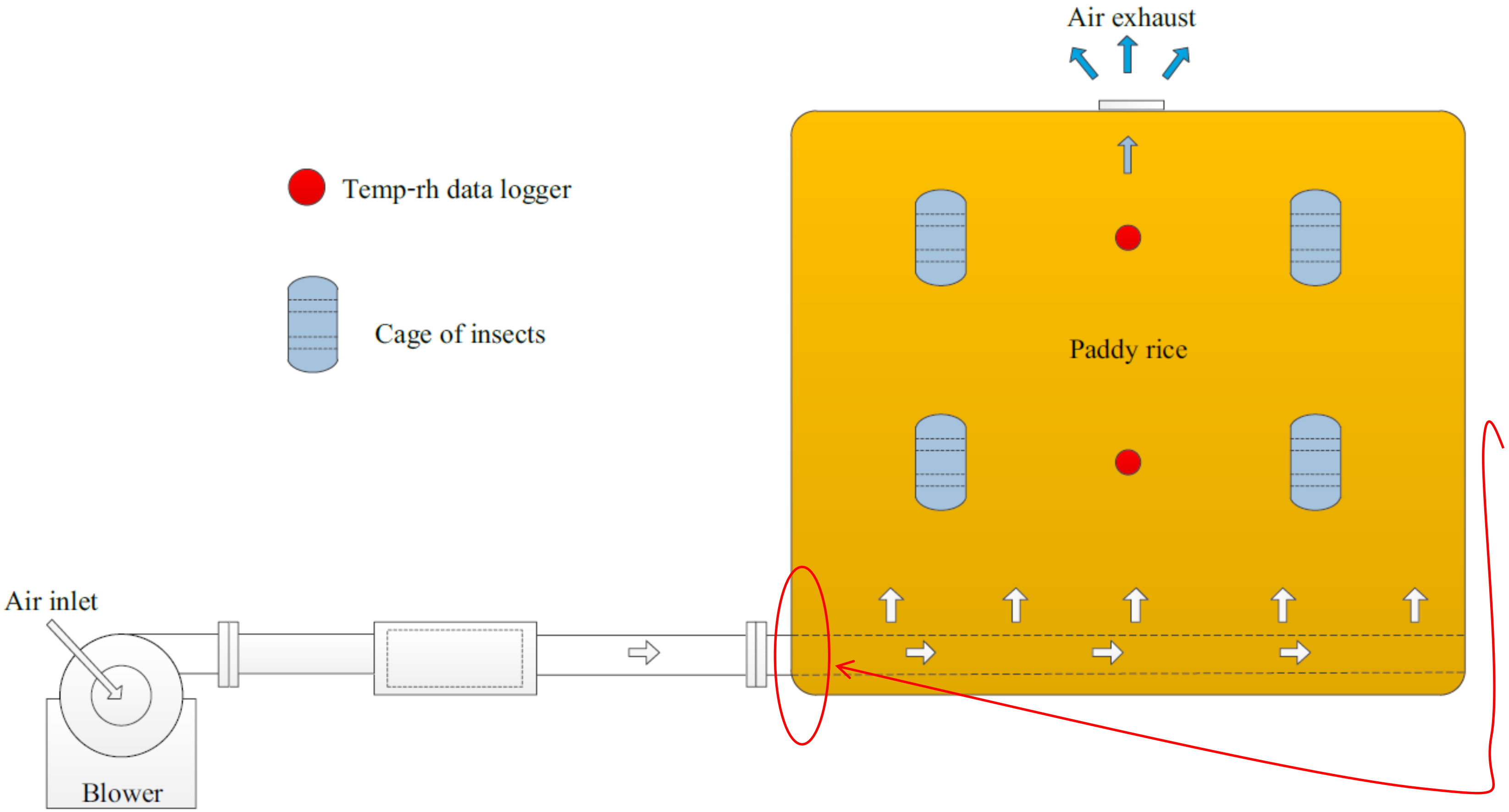

- Friction between the air and duct walls
- Flow through porous materials
- Changes in flow direction
- **Sudden changes in cross-sectional area**

What Causes Flow Resistance or Pressure Drop in a System?

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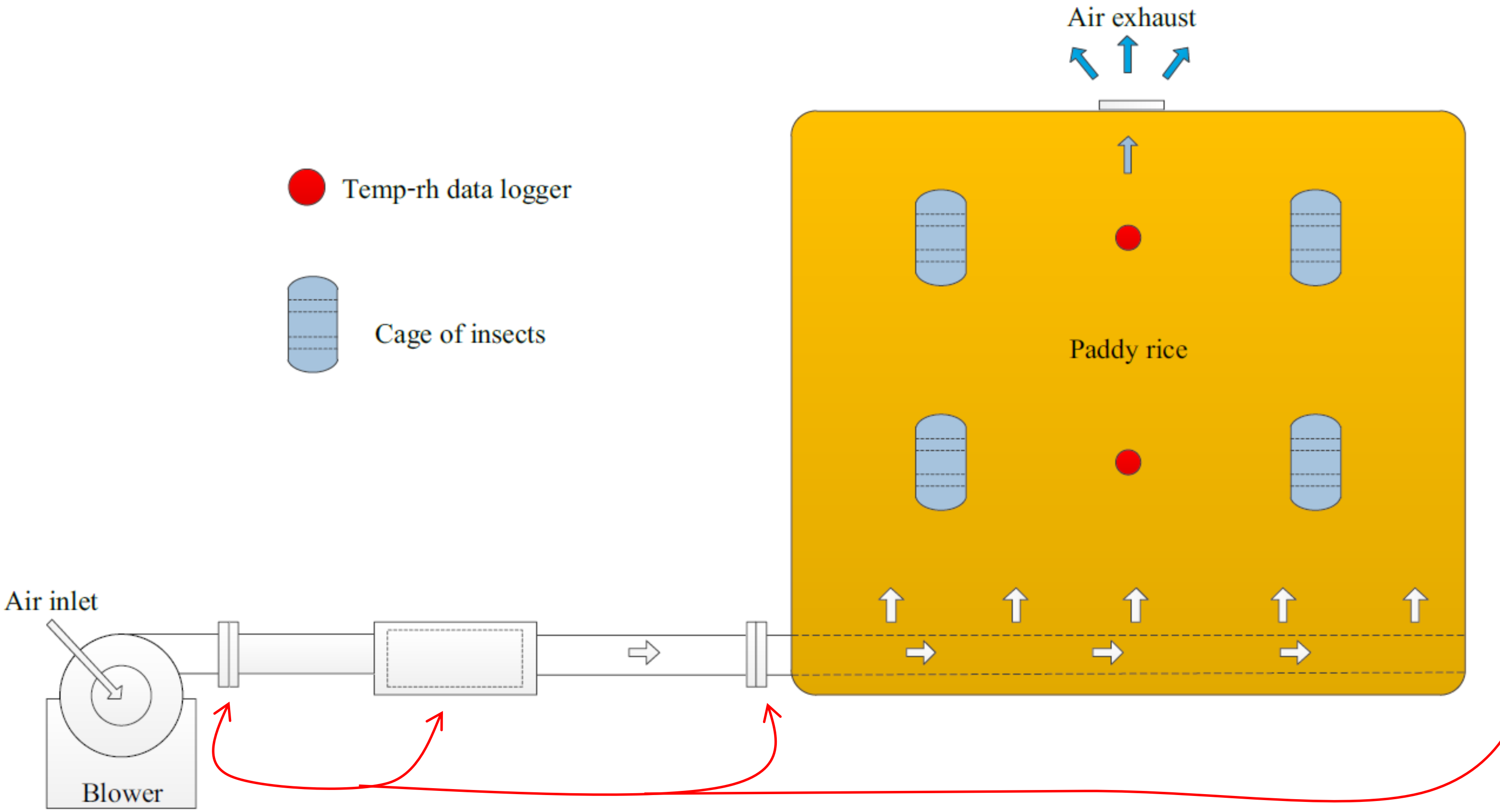

- Friction between the air and duct walls
- Flow through porous materials
- Changes in flow direction
- Sudden changes in cross-sectional area
- **Obstructions and fittings**

What Grain Properties Affect Pressure Drop in Grain Drying Systems?

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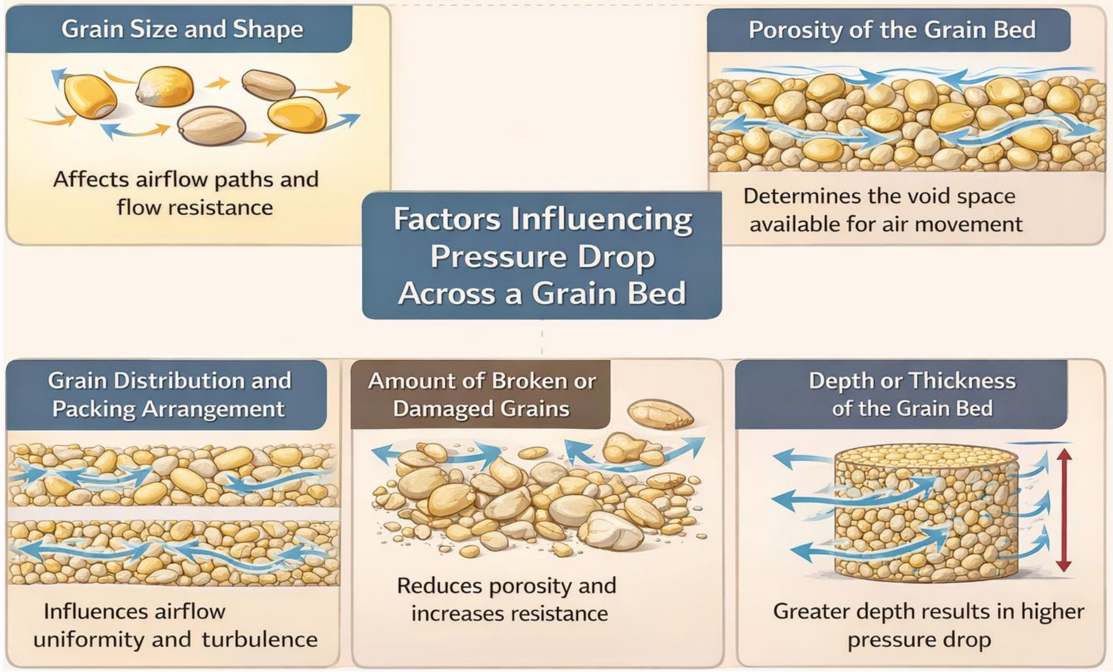
- ✓ Grain size and shape, which affect airflow paths and flow resistance
- ✓ Porosity of the grain bed, determining the void space available for air movement
- ✓ Grain distribution and packing arrangement, influencing airflow uniformity and turbulence
- ✓ Amount of broken or damaged grains, which reduces porosity and increases resistance
- ✓ Depth or thickness of the grain bed, where greater depth results in higher pressure drop



References: ChatGPT (OpenAI, 2023)

Resistance to Airflow for Other Agricultural Products

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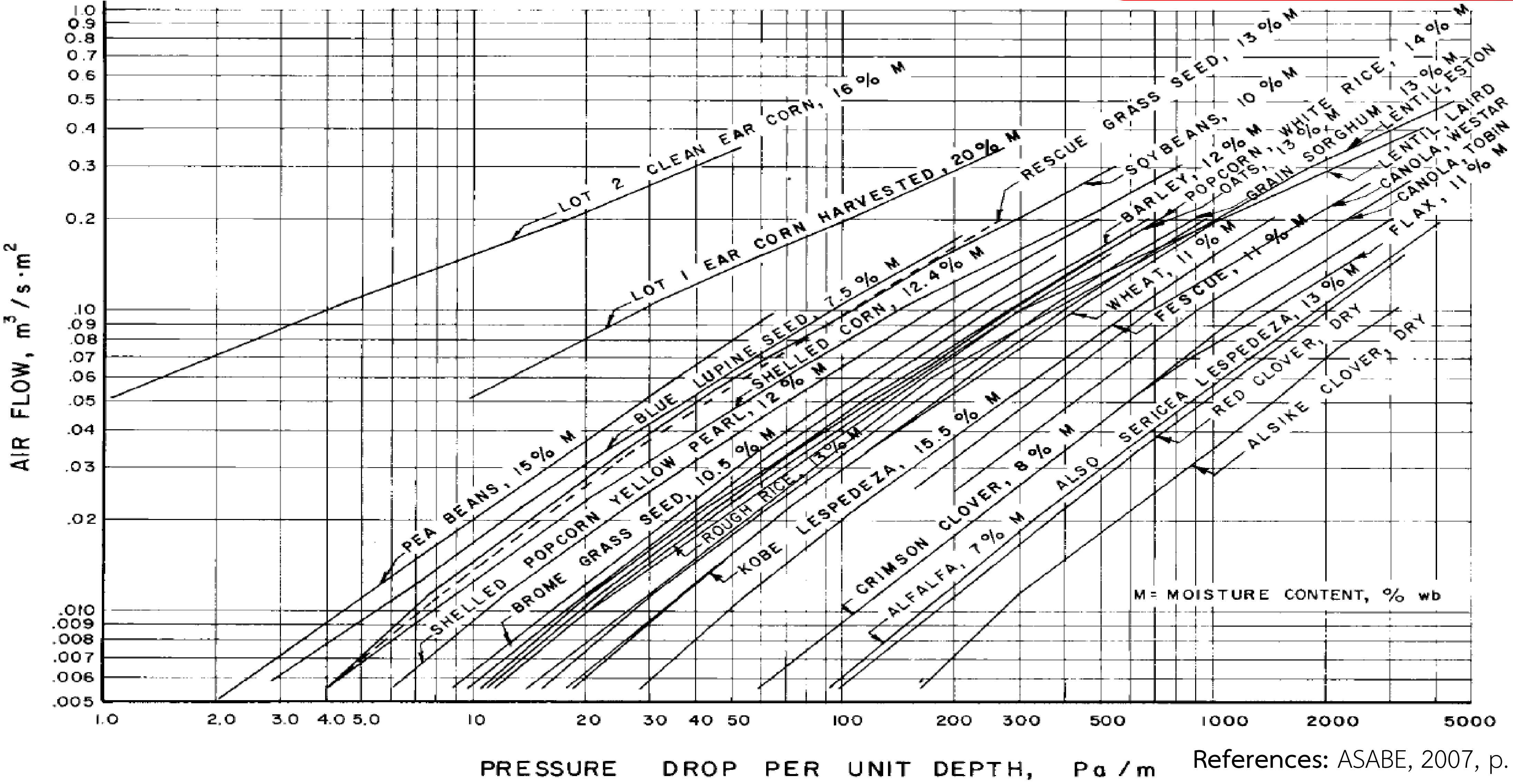
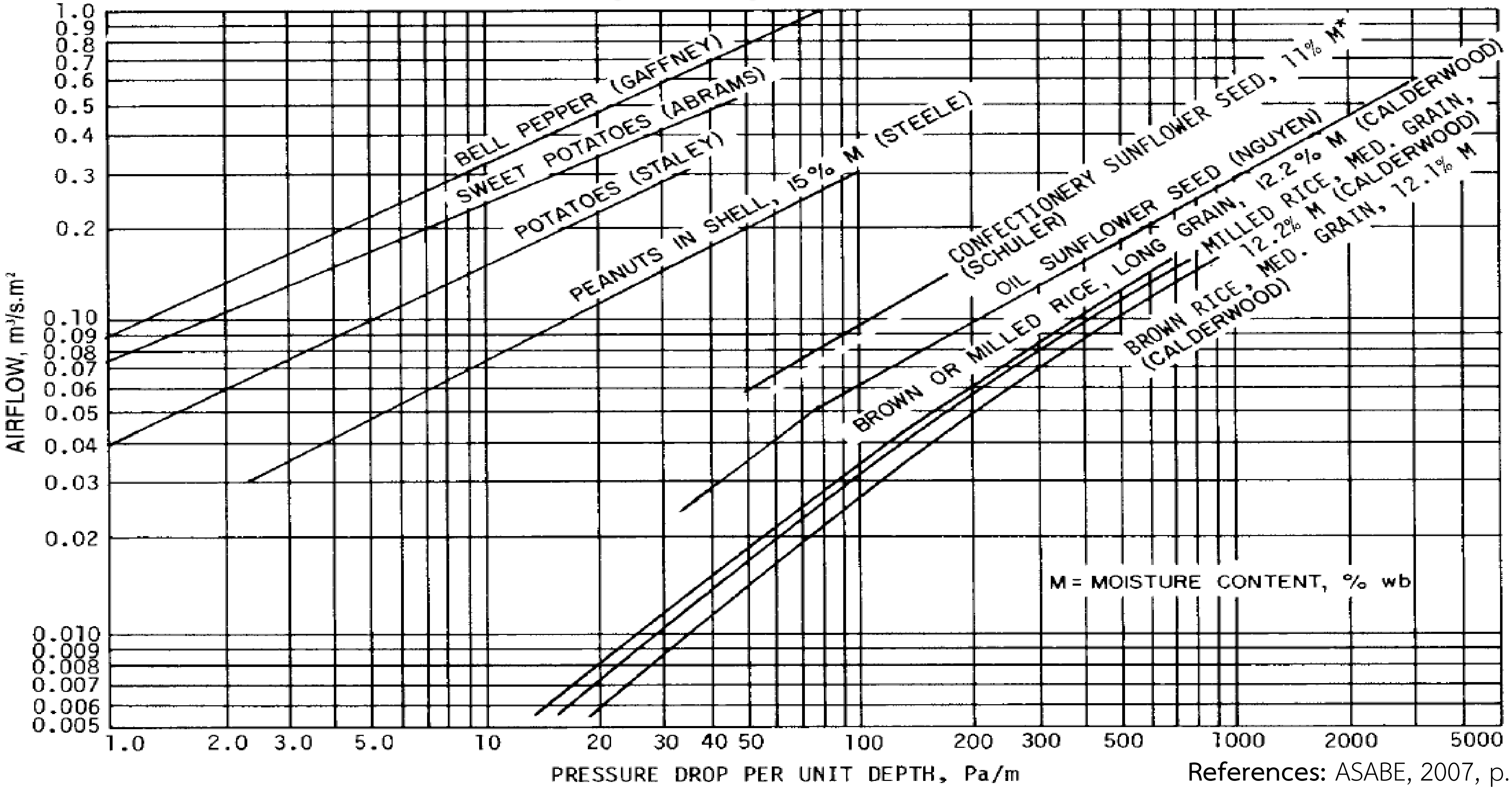


References: ASABE, 2007, p. 627

Resistance to Airflow for Other Agricultural Products (Cont.)



References: ASABE, 2007, p. 629

Airflow Resistance Equation

$$\Delta P = \frac{aQ^2}{\ln(1 + bQ)}$$

When

Q is airflow, $m^3 \cdot m^{-2} \cdot s^{-1}$

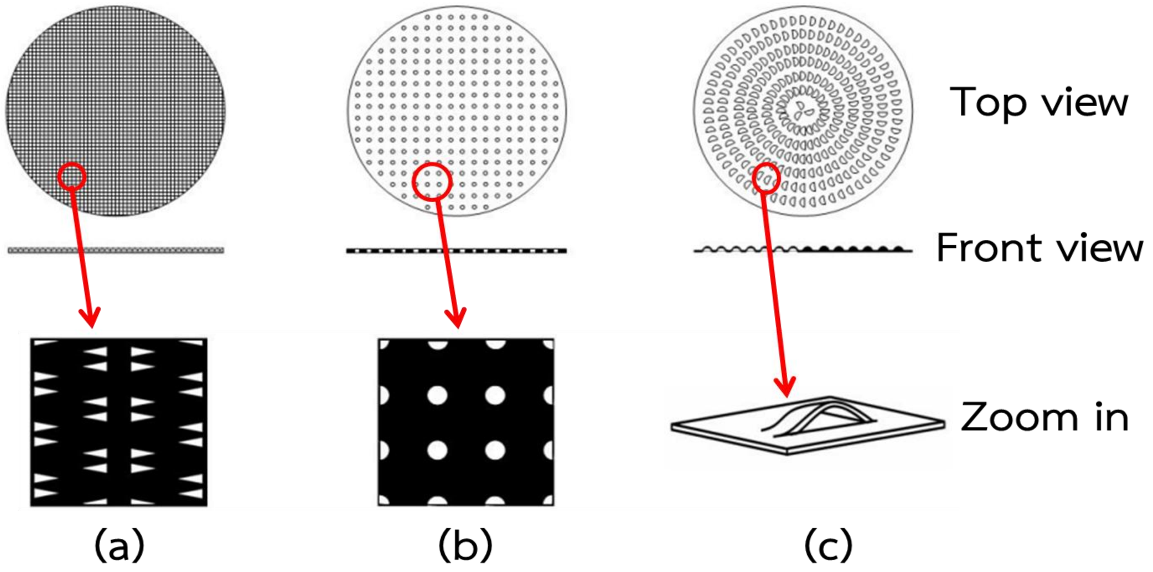
ΔP is pressure drop, Pa

a, b are constants for particular grain

Agricultural products	a $(Pa \cdot s^2 \cdot m^{-3})$	b $(m^2 \cdot s \cdot m^3)$	Q $(m^3 \cdot m^{-2} \cdot s^{-1})$
Barley	2.14×10^4	13.2	0.0056-0.203
Shelled corn	2.07×10^4	30.4	0.0056-0.304
Shelled corn (low airflow)	9.77×10^3	8.55	0.00025-0.0203
Oats	2.41×10^4	13.9	0.0056-0.203
Peanuts	3.80×10^3	111	0.030-0.304
Potatoes	2.18×10^3	824	0.030-0.300
Rough rice	2.57×10^4	13.2	0.0056-0.152
Sorghum	2.12×10^4	8.06	0.0056-0.203
Soybeans	1.02×10^4	16	0.0056-0.304
Sweet potatoes	3.40×10^3	6.1×10^8	0.050-0.499
Wheat	2.70×10^4	6.77	0.0056-0.203
Wheat (low airflow)	8.41×10^3	2.72	0.00025-0.0203

References: ASABE, 2007, p. 632

Pressure Drop Due to Perforated Plate



Dutch weave mesh   Perforated plate   Punched plate

$$\Delta P = 1.07\left[\frac{Q}{\varepsilon \times O_f}\right]^2$$

$$O_f = \frac{\textit{Total area of all holes}}{\textit{Surface area of plate}} \times 100\%$$

O_f = open area ratio of the perforated plate (expressed in decimal form)

For $O_f \geq 0.10$, the perforated plate loss is neglected

References: Wormsbecker et al., 2007, p. 817

Pressure Drop Due to a Straight Pipe

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Darcy-Weisbach equation

$$\Delta P = f \cdot \frac{L}{D} \cdot \frac{1}{2} \rho V^2$$

When

f is friction coefficient

D is diameter of pipe, m

V is air velocity, $m \cdot s^{-1}$

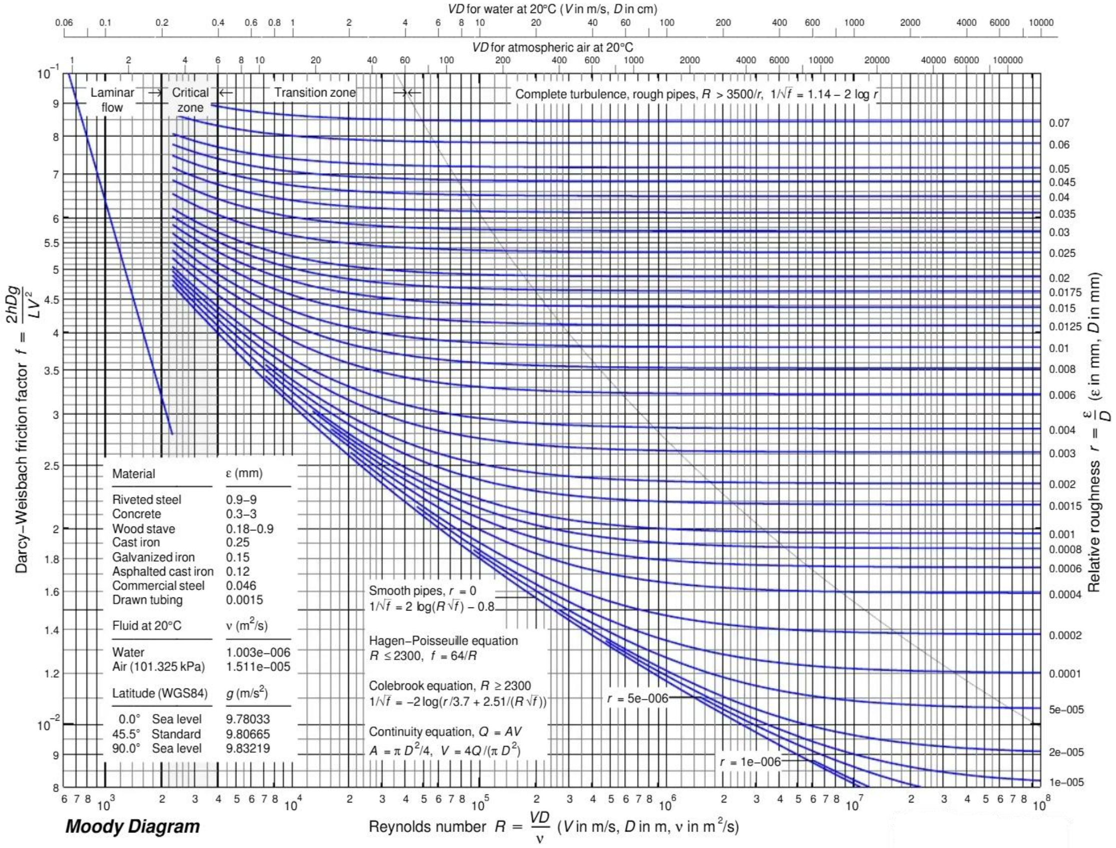
$\boldsymbol{\rho}$ is air density, $kg \cdot m^{-3}$

L is straight pipe length, m

ΔP is pressure drop, Pa

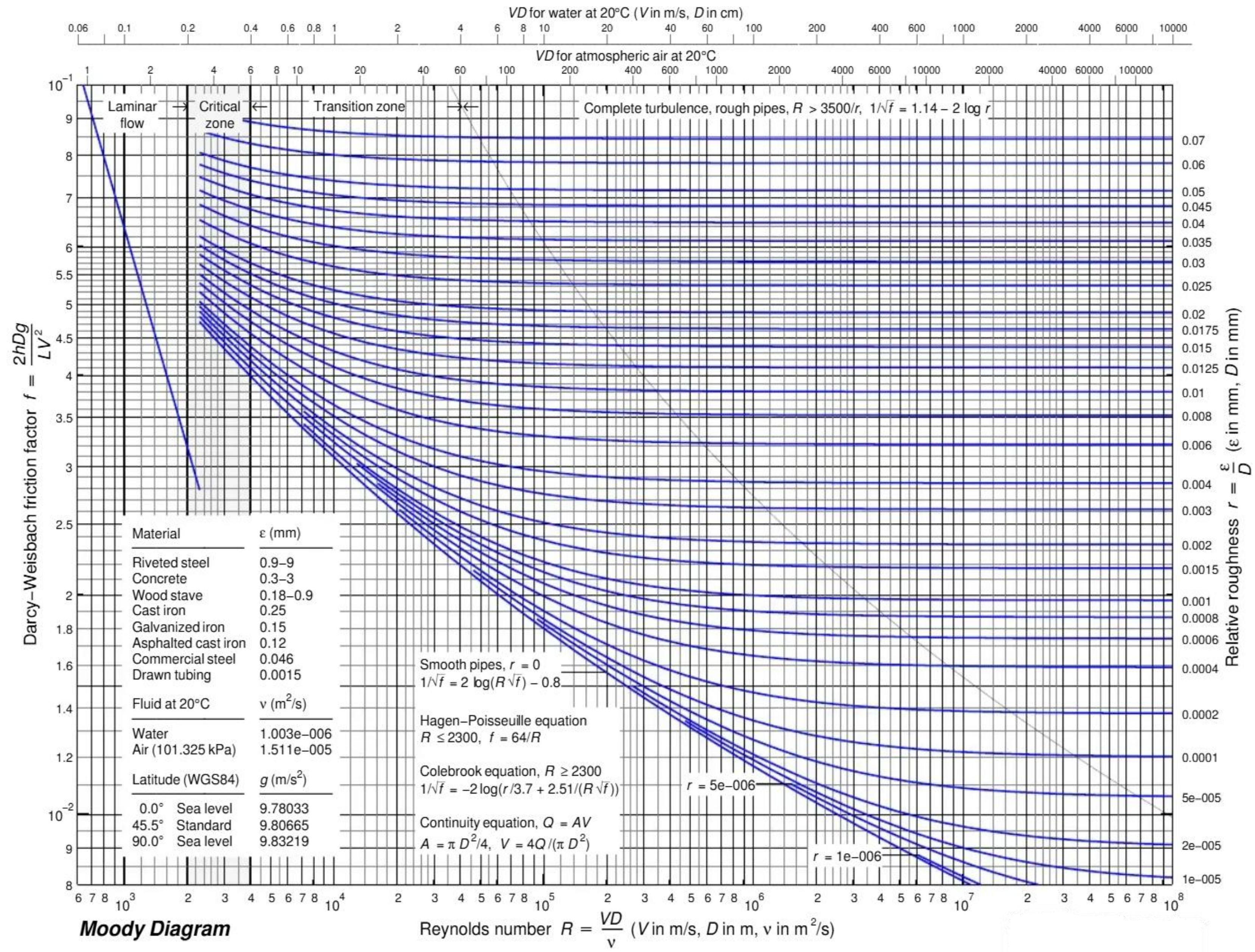
References: Metzger & Willard, n.d.

Moody diagram



Reynolds number (Re) & relative roughness $\frac{\varepsilon}{D}$)

ε is absolute roughness, m



Laminar flow (Re < 2,000)

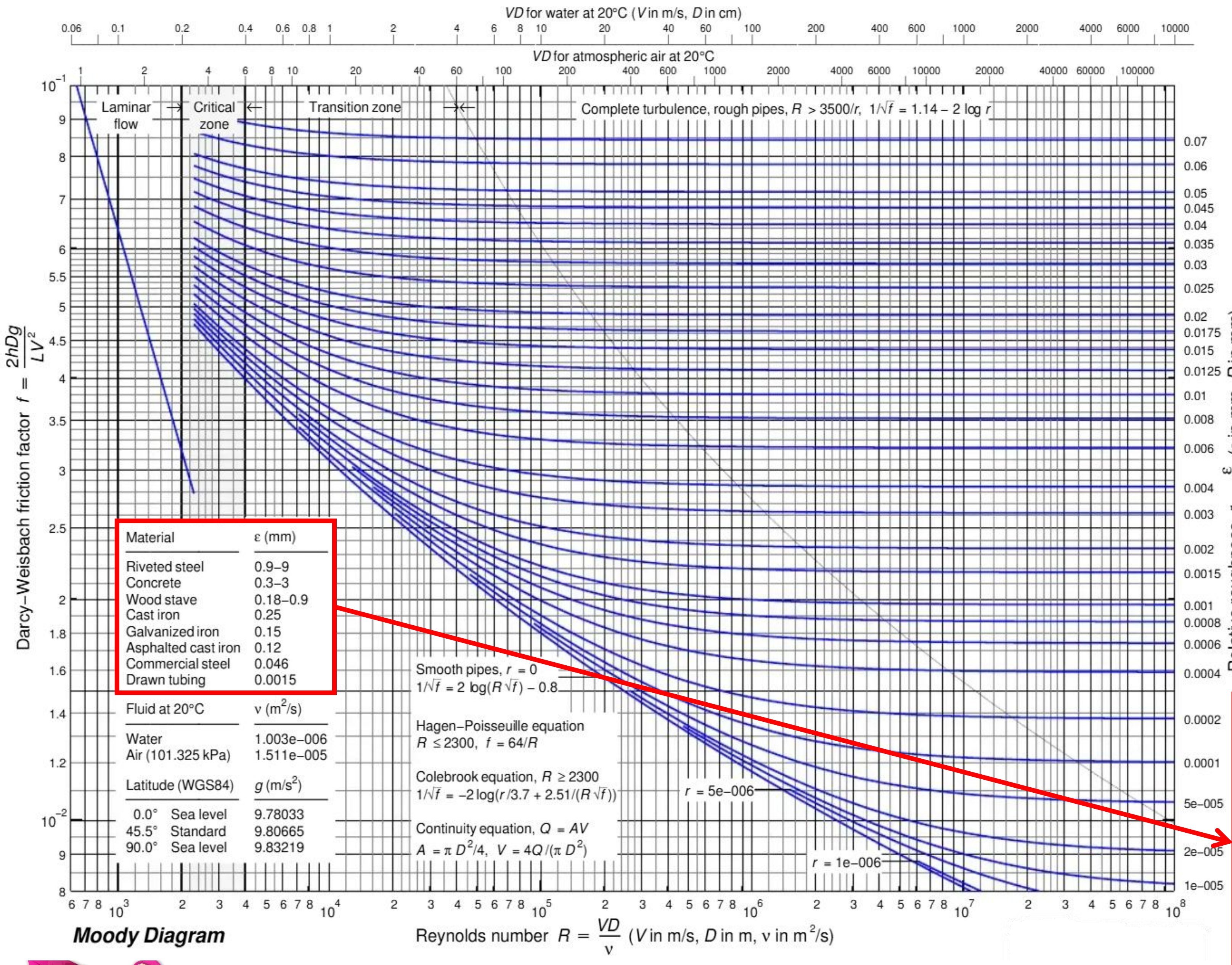
The friction coefficient is calculated as follows:

$$f = \frac{64}{\mathrm{Re}}$$

$$\mathrm{Re} = \frac{\rho \times V \times D}{\nu}$$

ν *is kinematic viscosity, $m^2 \cdot s^{-1}$*

(Kinematic viscosity of air =0.00001511 $m^2 \cdot s^{-1}$)



Transition zone

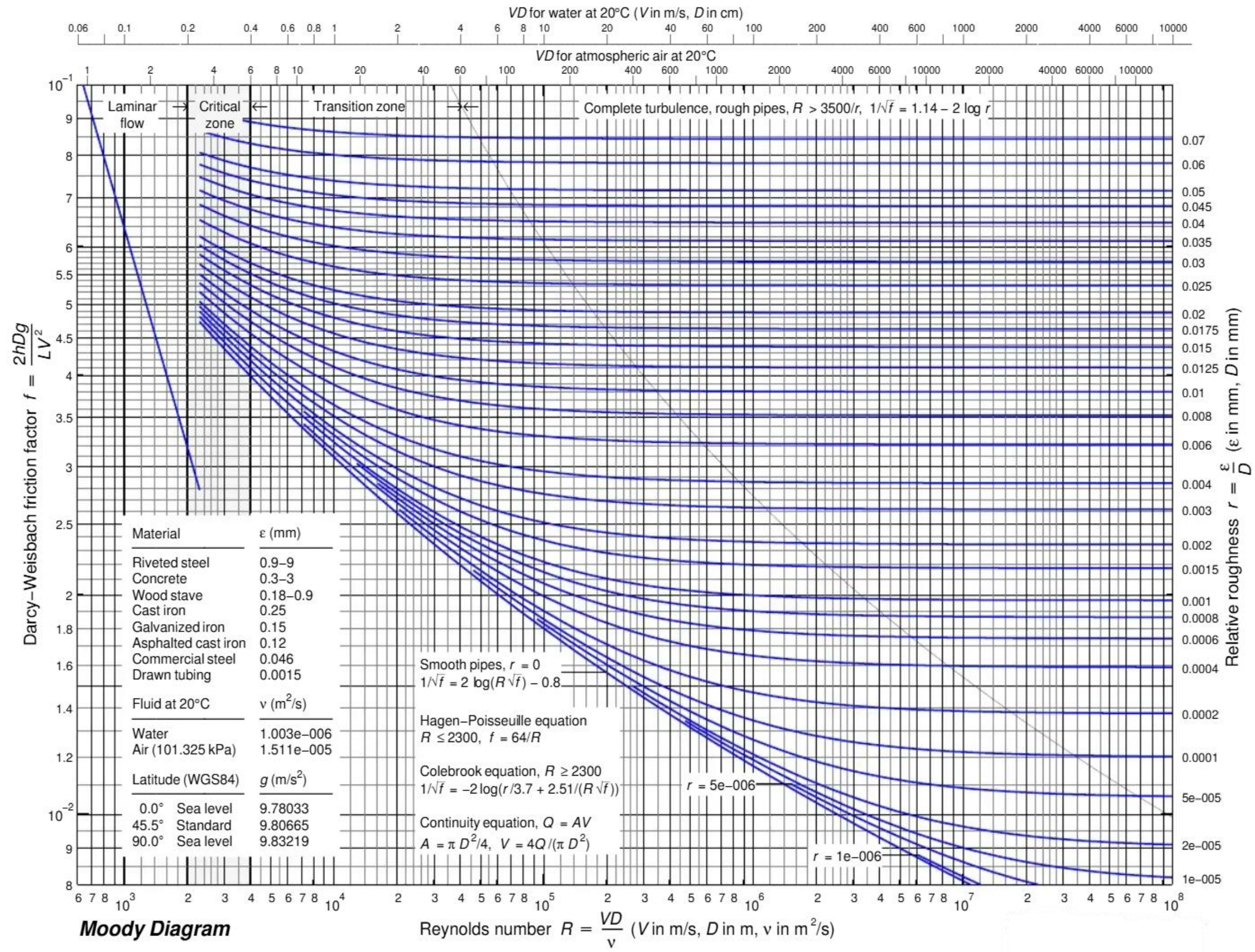
(2,000 < Re < 4,000)

Colebrook–White equation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right]$$

Material	ε (mm)
Riveted steel	0.9–9
Concrete	0.3–3
Wood stave	0.18–0.9
Cast iron	0.25
Galvanized iron	0.15
Asphalted cast iron	0.12
Commercial steel	0.046
Drawn tubing	0.0015

References: Metzger & Willard, n.d.



Turbulence

$(4{,}000 < Re < 100{,}000)$

For smooth pipe flow, f is calculated as follow:

$$f = \frac{0.3164}{Re^{0.25}}$$

For rough pipe flow, the friction factor f is calculated as follow:

$$\frac{1}{\sqrt{f}} = 1.14 + 2\log\left(\frac{D}{\varepsilon}\right)$$

References: Metzger & Willard, n.d.

The relationship between flow rate, pressure drop per unit pipe length (1 m), and the diameter of a circular pipe

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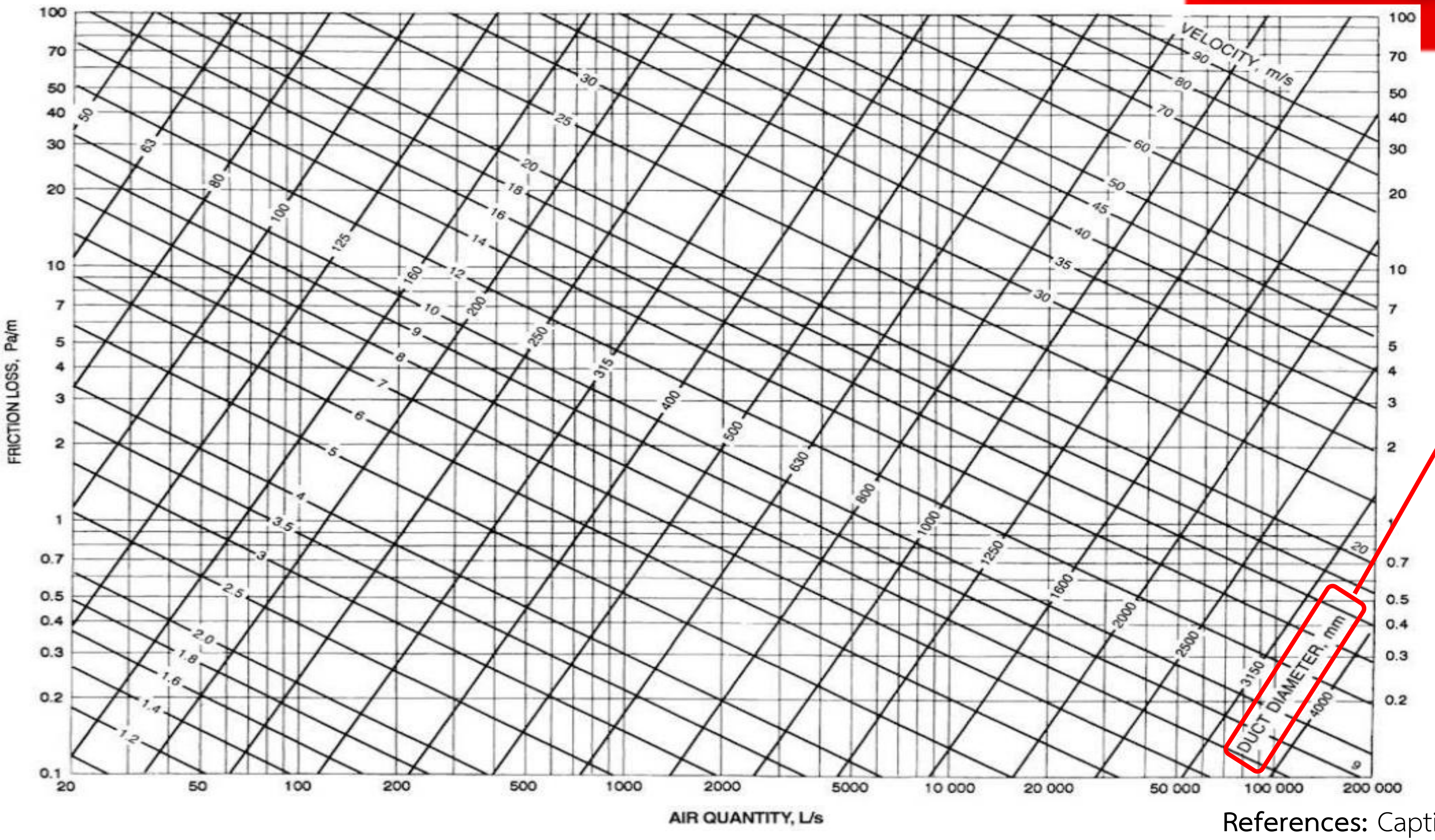


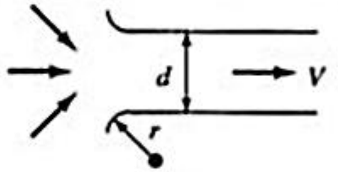
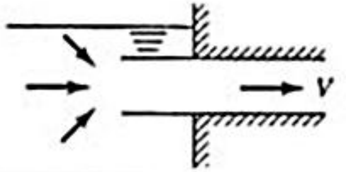
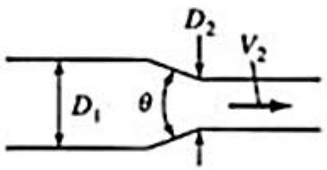
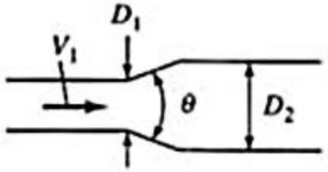
Non-circular air ducts

(e.g., rectangular ducts with dimensions *a* & *b*)

$$D = 1.265\sqrt[5]{\frac{(ab)^3}{(a+b)}}$$

References: Captiveair, n.d.

Pressure Drop Due to Pipe fittings

Description	Sketch	Additional Data	K	
Pipe entrance		r/d	K_e	
		0.0	0.50	
		0.1	0.12	
$h_L = K_e V^2/2g$		>0.2	0.03	
			1.00	
Contraction		D_2/D_1	K_C $\theta = 60°$	K_C $\theta = 180°$
		0.0	0.08	0.50
		0.20	0.08	0.49
		0.40	0.07	0.42
		0.60	0.06	0.32
		0.80	0.05	0.18
$h_L = K_C V_2^2/2g$		0.90	0.04	0.10
Expansion		D_1/D_2	K_E $\theta = 10°$	K_E $\theta = 180°$
		0.0		1.00
		0.20	0.13	0.92
		0.40	0.11	0.72
		0.60	0.06	0.42
$h_L = K_E V_1^2/2g$		0.80	0.03	0.16

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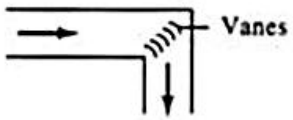
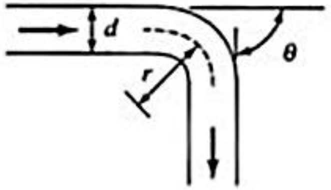
Description	Sketch	Additional Data	K	
90° miter bend		Without vanes	$K_b = 1.1$	
		With vanes	$K_b = 0.2$	
Smooth bend		r/d	K_b $\theta = 45°$	K_b $\theta = 90°$
		1	0.10	0.35
		2	0.09	0.19
		4	0.10	0.16
		6	0.12	0.21
Threaded pipe fittings	Globe valve - wide open		$K_v = 10.0$	
	Angle valve - wide open		$K_v = 5.0$	
	Gate valve - wide open		$K_v = 0.2$	
	Gate valve - half open		$K_v = 5.6$	
	Return bend		$K_b = 2.2$	
	Tee		$K_t = 1.8$	
	90° elbow		$K_b = 0.9$	
	45° elbow		$K_b = 0.4$	

$$\Delta P = K\left(\frac{V}{1.29}\right)^2$$

References: Ponce, n.d.

Example 1

A cylindrical silo contains an oat bed with a height of 4 m and a void fraction of 0.40. The oats are supported by a perforated steel plate with an open-area ratio (hole area to cross-sectional area) of 10%. The silo diameter is 8.5 m. In addition, an axial-flow fan is installed at the bottom of the silo and connected to a duct of 6 m length and 0.6 m diameter.

Determine

- the total pressure loss and the required static pressure when the air flow rate is 50 $m^3 \cdot min^{-1}$ at an air temperature of 30°C.

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Solution:

the pressure losses in the system consist of:

- *Pressure loss across the grain bed with a depth of 4 m*
- *Pressure loss across the perforated plate*
- *Entrance loss at the inlet of the under-bin air plenum*
- *Pressure loss in a straight pipe*

Example 1 (Cont.)

Pressure loss across <u>the grain bed with a depth </u>of 4 m

$$\Delta P = \frac{aQ^2}{\ln(1+bQ)}$$

Q is airflow, $m^3 \cdot m^{-2} \cdot s^{-1}$

Air flow rate is **<u>50 m³·min⁻¹</u>**

Agricultural products	a ($Pa \cdot s^2 \cdot m^{-3}$)	b ($m^2 \cdot s \cdot m^3$)	Q ($m^3 \cdot m^{-2} \cdot s^{-1}$)
Barley	2.14×10^4	13.2	0.0056-0.203
Shelled corn	2.07×10^4	30.4	0.0056-0.304
Shelled corn (low airflow)	9.77×10^3	8.55	0.00025-0.0203
Oats	2.41×10^4	13.9	0.0056-0.203

$$Q = \frac{\frac{50}{60}}{\frac{\pi}{4} \times 8.5^2} = 0.01468 \ m^3 \cdot s^{-1} m^{-2}$$

$$\Delta P = \frac{2.41 \times 10^4 \times 0.01468^2}{\ln(1+(13.9 \times 0.01468))} \times 4 = 111.86 \ Pa$$

Example 1 (Cont.)

Pressure loss across the perforated plate

When:

Void fraction of 0.40 $\varepsilon = 0.40$

Open-area ratio (hole area to cross-sectional area) of 10%

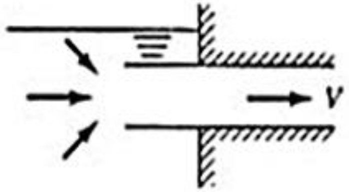
$$O_f = 0.1$$

$$\Delta P = 1.07\left(\frac{Q}{O_f \times \varepsilon}\right)^2 = 1.07\left(\frac{0.01468}{0.40 \times 0.1}\right)^2 = 0.144 \; Pa$$

Example 1 (Cont.)

<u>Entrance</u> loss at the inlet of the under-bin air plenum

When: K= 0.1

Description	Sketch	Additional Data	K
Pipe entrance			1.00

$$V = \frac{Q}{A} = \frac{\frac{50}{60}}{\frac{\pi}{4} \times 0.6^2} = 2.947 \; m \cdot s^{-1}$$

$$\Delta P = K\left(\frac{V}{1.29}\right)^2 = 1.0\left(\frac{2.947}{1.29}\right)^2 = 5.22 \; Pa$$

Example 1 (Cont.)

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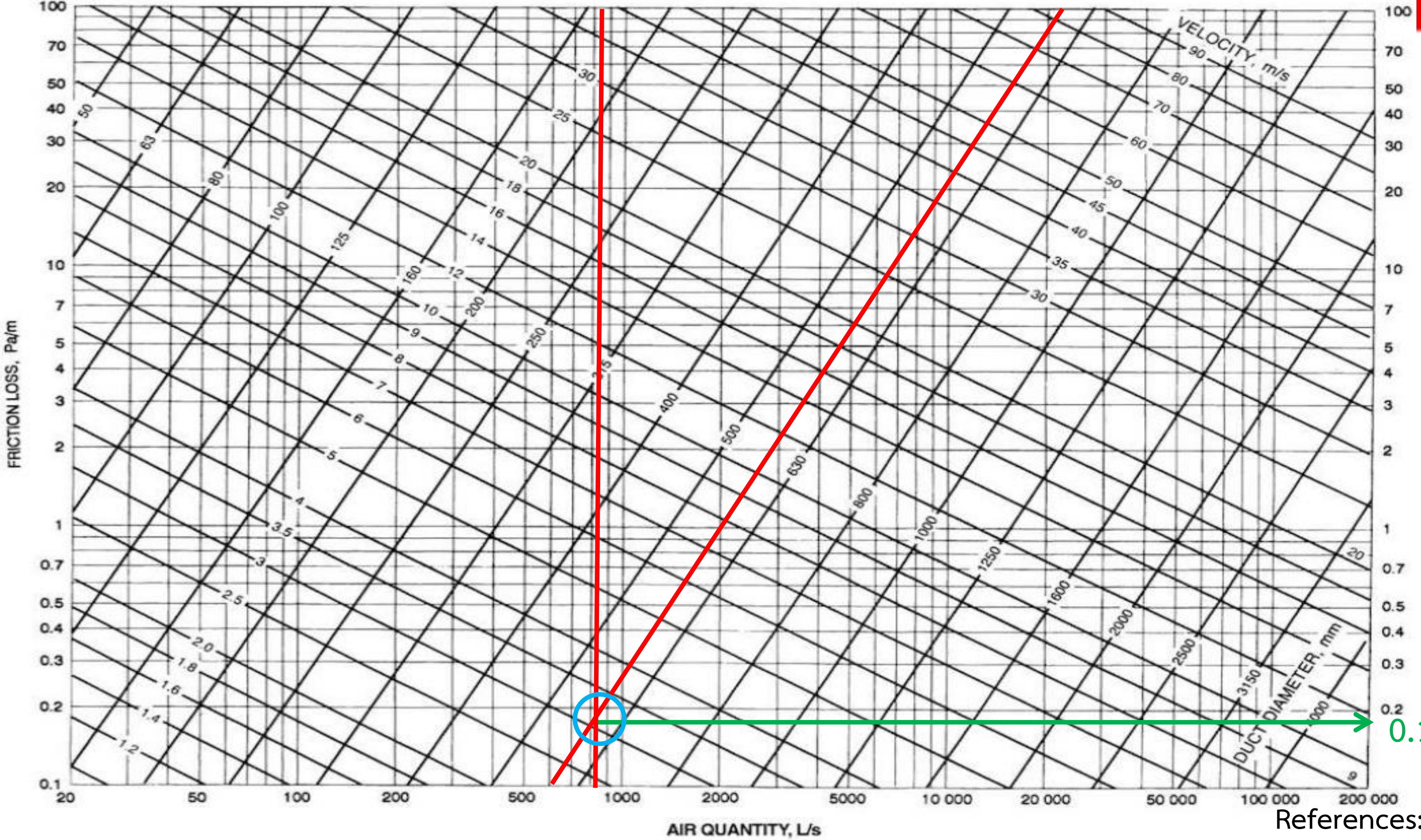
Pressure loss in a straight pipe



Q = 50 m^3 min^{-1} = 833 l s^{-1}

Diameter of pipe = 600 mm

Friction loss = **0.18 Pa·m^{-1}**

Length of pipe = **6 m**

$$\Delta P = 0.18 \times 6 = 1.08\ Pa$$

References: Captiveair, n.d.

Example 1 (Cont.)

A cylindrical silo contains an oat bed with a height of 4 m and a void fraction of 0.40. The oats are supported by a perforated steel plate with an open-area ratio (hole area to cross-sectional area) of 10%. The silo diameter is 8.5 m. In addition, an axial-flow fan is installed at the bottom of the silo and connected to a duct of 6 m length and 0.6 m diameter.

Determine

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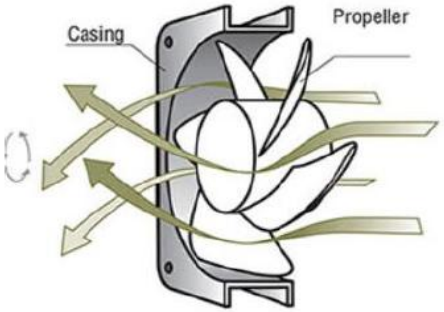
The total pressure loss:

$$\boxed{111.86+0.144+5.22+1.08 = 118.304 \text{ Pa}}$$



Fan (Axial-Flow Fan)

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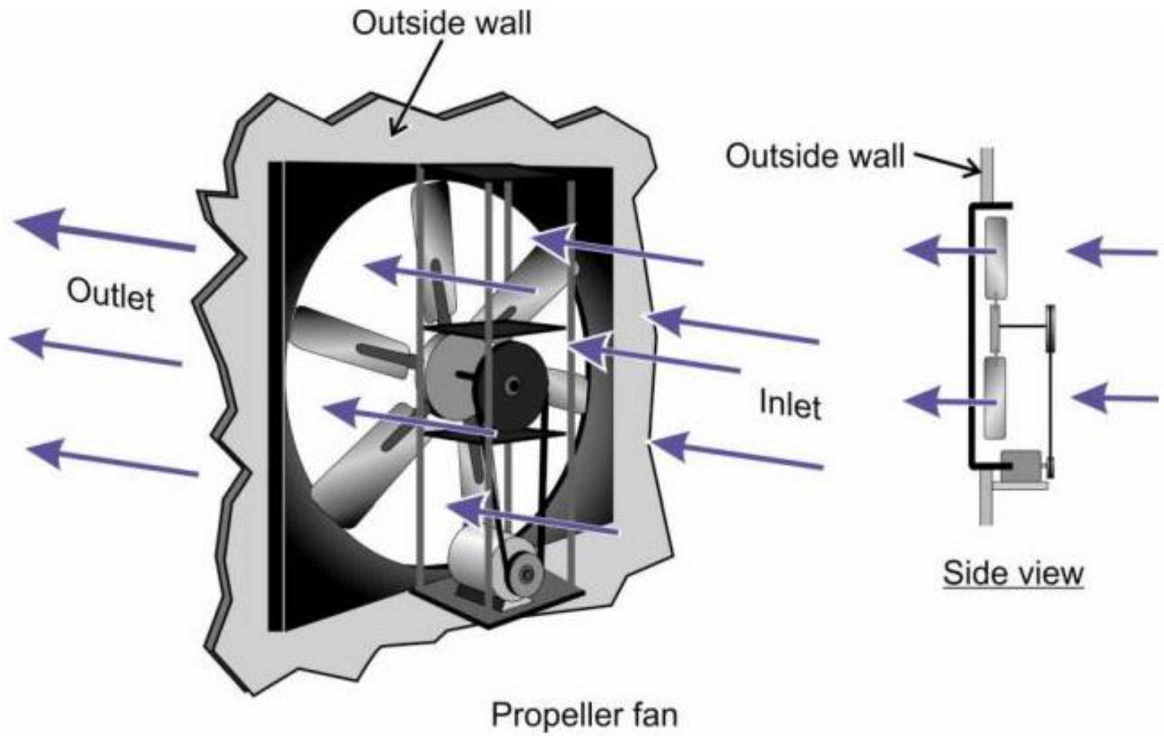

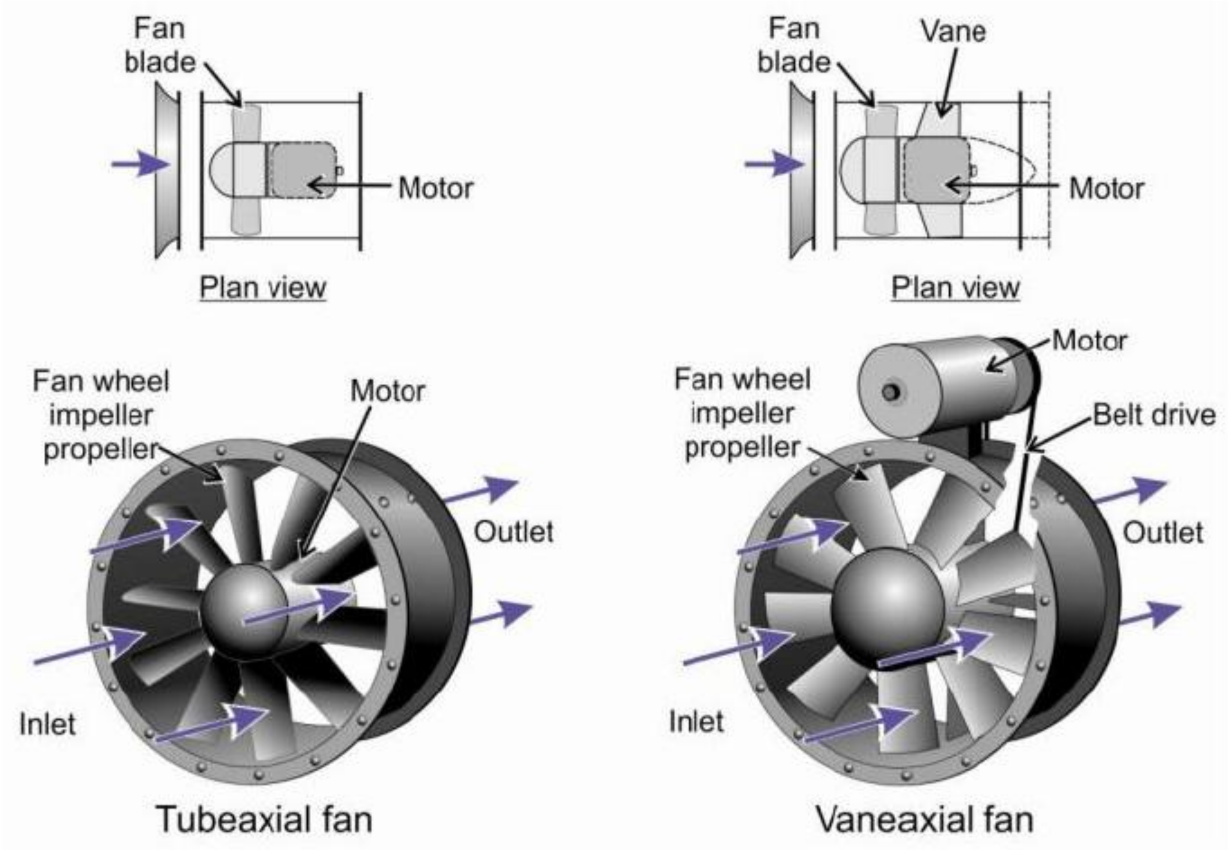

References: Cecala et al., 2012, p. 64, Oriental motor, n.d., Aerovent, n.d.

Fan (Centrifugal Fan)

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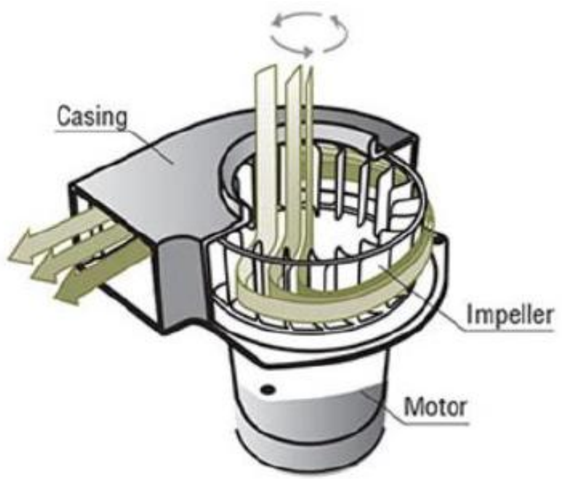

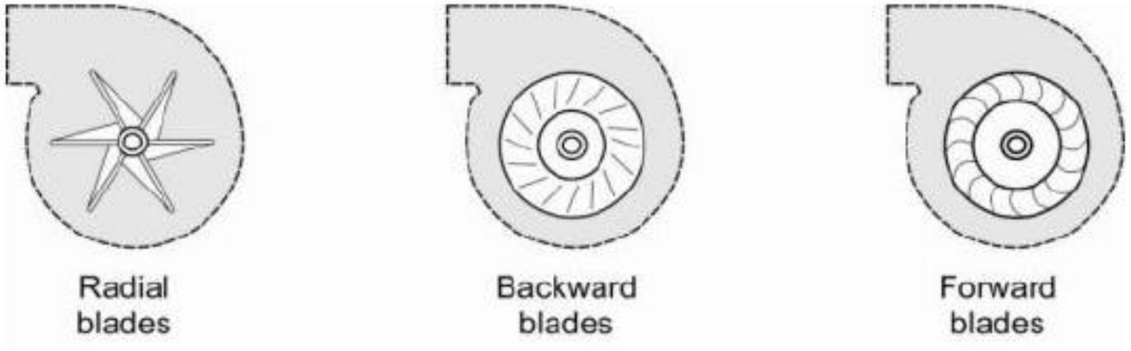

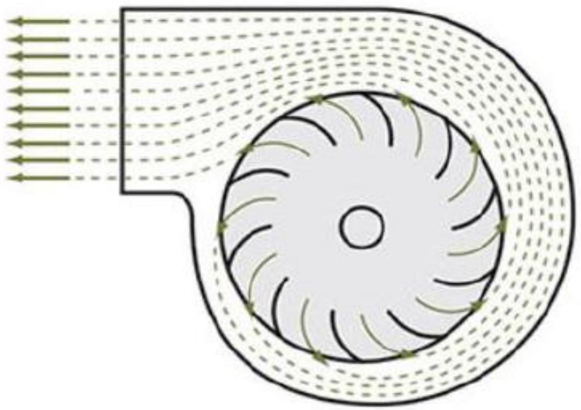

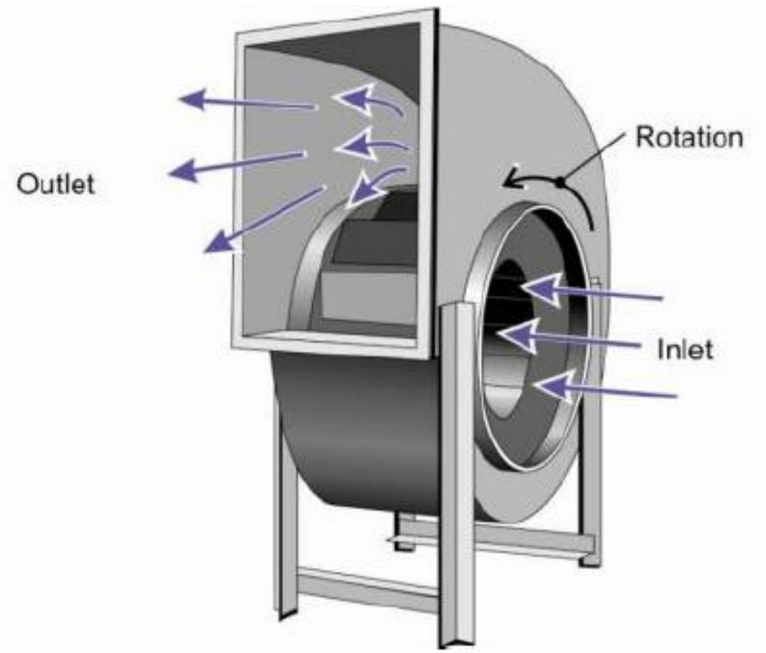

References: Cecala et al., 2012, p. 64, Oriental motor, n.d., Aerovent, n.d.

Comparison of Cost, Pressure, and Noise Levels of Different Fan Types

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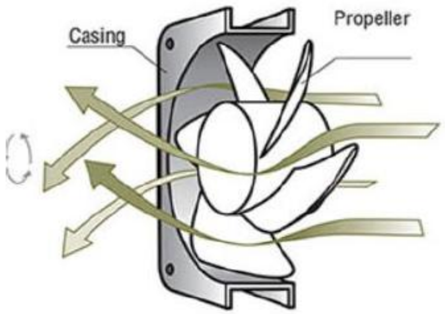

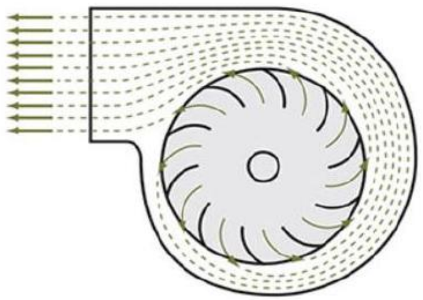

Comparison	Axial-flow fan	Centrifugal fan	
		Forward	Backward
Price	Lowest	Medium	Highest
Pressure	Low–Medium	Low–Medium	Highest
Voice	Highest	Medium	Low

References: Oriental motor, n.d., Aerovent, n.d.

Fan Performance

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Key Fan Performance Definitions

- **Fan total pressure (P_t)**: Pressure difference between fan outlet and inlet
- **Fan static pressure (P_s)**: Difference between total pressure and velocity pressure
- **Fan velocity pressure**: Pressure due to air velocity at the fan outlet
- **Air power**: Product of pressure and airflow rate. It can be calculated in two forms according to Equations:

(total power, W_t) (Watt) $$W_t = P_t \times Q$$

(static power, W_s) (Watt) $$W_s = P_s \times Q$$

Fan Performance

Key Fan Performance Definitions

- **Fan efficiency** is the ratio of the output power delivered by the fan to the input power supplied to the fan. It is usually expressed as a percentage

- Two types of fan efficiency are defined:

Total fan efficiency

$$\eta_t = \frac{total\ \ power}{input\ \ power} \times 100\% = \frac{W_t}{W_I} \times 100\%$$

Static fan efficiency

$$\eta_s = \frac{static\ \ power}{input\ \ power} \times 100\% = \frac{W_s}{W_I} \times 100\%$$

Example 2

During storage, aeration is performed with an airflow rate of 3 $m^3 \cdot s^{-1}$. The total friction loss results in a pressure drop of 405 Pa. Assuming a total fan efficiency of 80%, determine the required fan power

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Given: P_t = 405 Pa = 405 $N \cdot m^{-2}$ Q = 3 $m^3 \cdot s^{-1}$

(total power, W_t) (Watt) $W_t = P_t \times Q$

$$W_t = 405\ N \cdot m^{-2} \times 3\ m^3 \cdot s^{-1} = 1{,}215\ Watt$$

$$\eta_t = \frac{total\ \ power}{input\ \ power} \times 100\% = \frac{W_t}{W_i} \times 100\%$$

$$80\% = \frac{1{,}215\ \ Watt}{input\ \ power} \times 100\%$$

$$input\ \ power = \frac{1{,}215\ \ Watt}{80} \times 100\% = 1{,}518.75\ \ Watt$$

Centrifugal Fan Laws

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Same fan with a different rotational speed

$$\frac{N_1}{N_2} = \frac{Q_1}{Q_2}$$

$$\frac{(N_1)^2}{(N_2)^2} = \frac{P_1}{P_2}$$

$$\frac{(N_1)^3}{(N_2)^3} = \frac{W_1}{W_2}$$

Fan with a different impeller diameter at constant rotational speed

$$\frac{(D_1)^3}{(D_2)^3} = \frac{Q_1}{Q_2}$$

$$\frac{(D_1)^2}{(D_2)^2} = \frac{P_1}{P_2}$$

$$\frac{(D_1)^5}{(D_2)^5} = \frac{W_1}{W_2}$$

In actual operating conditions, a fan may experience changes in rotational speed or impeller diameter, which can affect the airflow

$$\frac{N_1}{N_2} \cdot \frac{(D_1)^3}{(D_2)^3} = \frac{Q_1}{Q_2}$$

$$\frac{(N_1)^2}{(N_2)^2} \cdot \frac{(D_1)^2}{(D_2)^2} = \frac{P_1}{P_2}$$

$$\frac{(N_1)^3}{(N_2)^3} \cdot \frac{(D_1)^5}{(D_2)^5} = \frac{W_1}{W_2}$$

when

N: the rotational speed of the fan (rpm)

D: the fan diameter (m)

Performance curves of centrifugal fans

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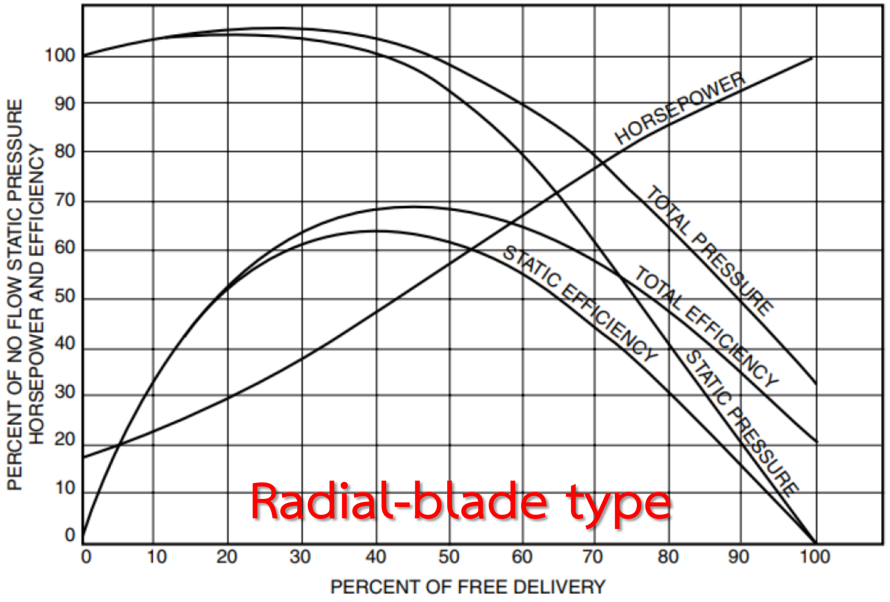
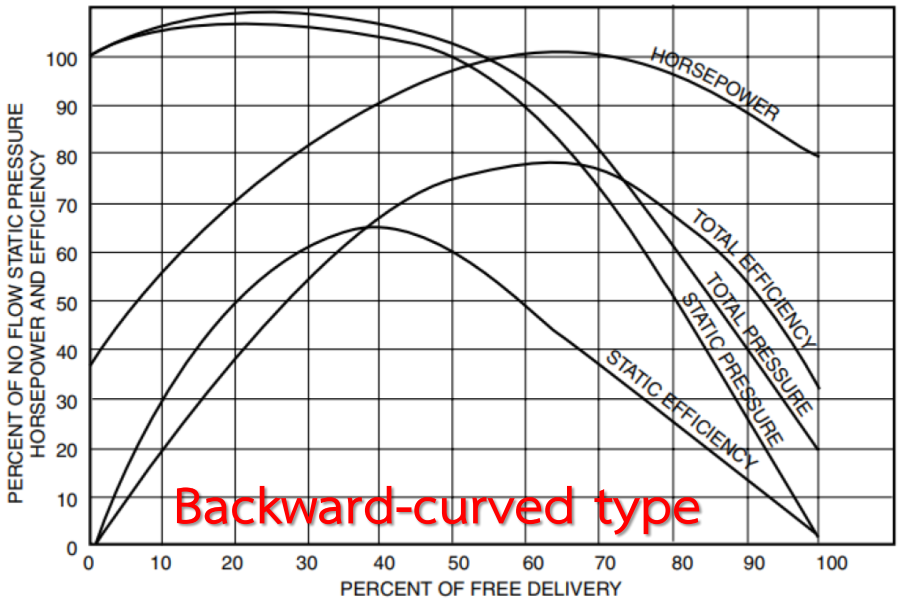
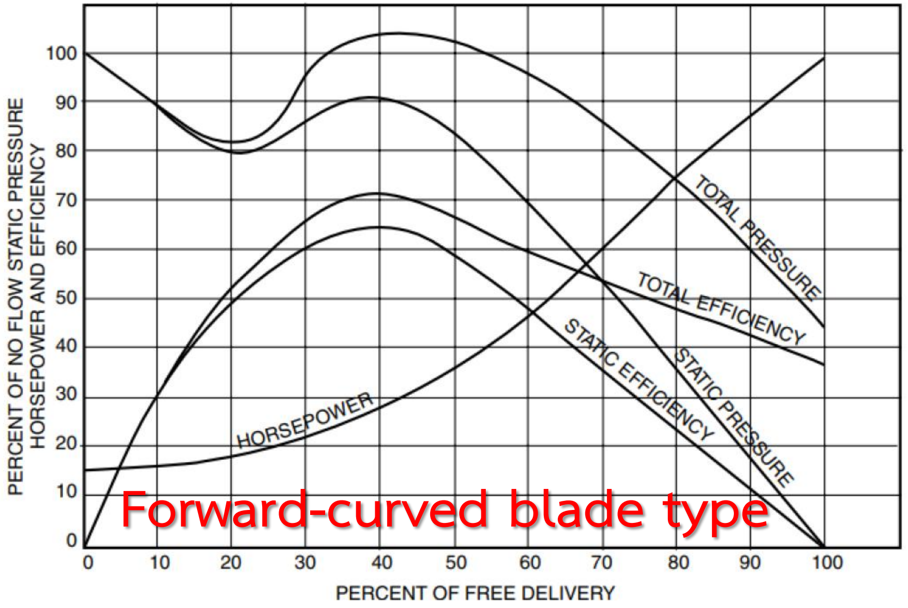
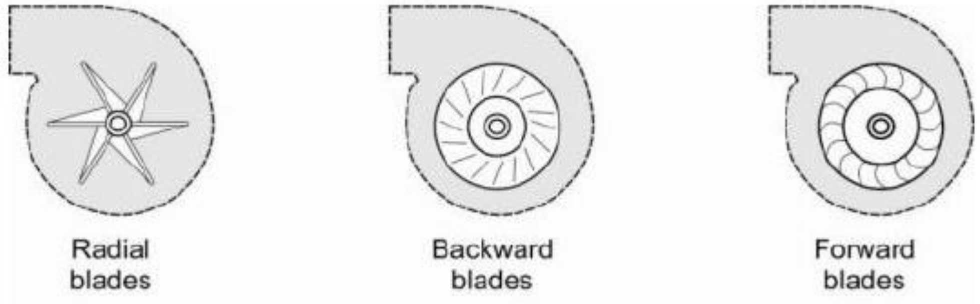






Adequate air pressure and airflow rate are key factors in selecting a suitable fan for drying applications



References: Aerovent, n.d.

Example 3

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A centrifugal fan with an impeller diameter of 1.1 m operates at a rotational speed of 1,100 rpm, delivering an airflow rate of 3 $m^3 \cdot s^{-1}$ at a pressure of 350 Pa. The fan performance data are given in the table. If a geometrically similar fan is required to operate at a pressure of 450 Pa with a reduced airflow rate of 0.5 $m^3 \cdot s^{-1}$, determine the impeller diameter, fan rotational speed, and the required fan power.

Q ($m^3 \cdot s^{-1}$)	P_s (Pa)	*Input power* (Watt)
0	350	500
1	387.5	750
2	400	1,250
3	375	1,500
4	325	1,750
5	237.5	1,975
6	112.5	1,950

Given:

D_1 = 1.1 m, N_1 = 1,100 rpm, Q_1 = 3 $m^3 \cdot s^{-1}$, Q_2 = 0.5 $m^3 \cdot s^{-1}$,

P_1 = 350 Pa P_2 = 450 Pa

$$\boxed{\frac{N_1}{N_2} \cdot \frac{(D_1)^3}{(D_2)^3} = \frac{Q_1}{Q_2}}$$

$$\boxed{\frac{(N_1)^2}{(N_2)^2} \cdot \frac{(D_1)^2}{(D_2)^2} = \frac{P_1}{P_2}}$$

$$D_2 = 1.1\left(\frac{3}{0.5}\right)^{\frac{1}{2}} \cdot \left(\frac{350}{450}\right)^{\frac{1}{4}} = 0.42\ m$$

$$N_2 = 1{,}100\left(\frac{3}{0.5}\right)^{\frac{1}{2}} \cdot \left(\frac{450}{350}\right)^{\frac{3}{4}} = 3{,}253\ rpm$$

$$\boxed{\frac{(N_1)^3}{(N_2)^3} \cdot \frac{(D_1)^5}{(D_2)^5} = \frac{W_1}{W_2}}$$

$$W_2 = 1{,}500\left(\frac{3{,}253}{1{,}100}\right)^{3} \cdot \left(\frac{0.42}{1.1}\right)^{5} = 314.8\ Watt$$

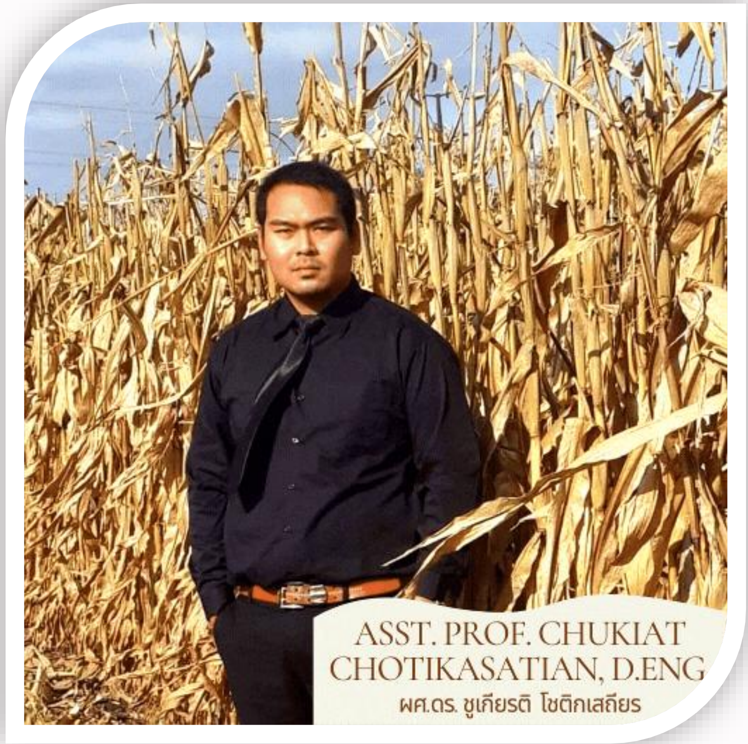
Summary

1. Methods for calculating pressure losses in drying systems

2. Sources of pressure loss, including depth and low porosity of grain beds, open area of perforated screens, type and configuration of air ducts

3. Types of fans (axial-flow fans & Centrifugal fans)

4. Comparison and calculation of electrical power requirements and airflow rate



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Thank you very much for your kind attention.

Questions?

Email: chukiat@webmail.npru.ac.th

Office: ETB 101 - Industrial Education, Faculty of Science and Technology

Study Questions – Lecture 3

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1. Why is airflow resistance important in agricultural drying systems?
2. What factors contribute to pressure drop in grain beds and air ducts?
3. How can airflow resistance be calculated in drying systems?
4. How are fans selected based on airflow and pressure requirements?

Assignment – Lecture 3

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1. A cylindrical bin with a diameter of 4 m contains a 2.5 m deep bed of paddy rice. The bin is connected to a cylindrical duct that is 6 m long with a duct diameter of 0.5 m. Calculate the static pressure loss when the volumetric flow rate is 2 $m^3 \cdot s^{-1}$.

2. In a grain-aeration system for a cylindrical bin, an operating fan runs at 1,350 rpm and produces a static pressure of 735.48 Pa. The required fan power is 14 W. If the fan speed is increased to 1,800 rpm, determine the airflow rate, static pressure, and fan power.

3. A centrifugal fan with an impeller diameter of 0.75 m operates at 1,300 rpm, delivering an airflow rate of 4 $m^3 \cdot s^{-1}$ at a pressure of 550 Pa. The fan performance data are provided in the table. If a geometrically similar fan is required to operate at a pressure of 750 Pa while the airflow rate decreases to 2.5 $m^3 \cdot s^{-1}$, determine the impeller diameter, fan rotational speed, and the required fan power.

Q ($m^3 \cdot s^{-1}$)	P_s (Pa)	*Input power* (Watt)
0	350	500
1	387.5	750
2	400	1,250
3	375	1,500
4	325	1,750
5	237.5	1,975
6	112.5	1,950

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