Physical and Thermal Properties of Grains

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Environmental Physical Factors in Post-Harvest Quality

- Stored food, both perishable and durable, may be considered to be an **ecosystem**, i.e. a system that includes a group of organisms and their environment

- The **interactions** between the physical, chemical and biological factors within the ecosystem lead to changes in the quality and nutritive value of the stored product

- Knowledge of these factors is therefore essential if the **quality** and **quantity** of stored products are to be maintained

- Data on physical properties of grain are essential for the design of **equipment** for handling, aeration, drying, and storage, as well as processing cereal grains and other agricultural materials

- Basic thermal and moisture transport properties are also required for **simulating heat and moisture transport** phenomena during **drying and storage**

The most important physical and thermal properties are:

- Grain weight
- Sphericity and roundness
- Size
- Volume
- Shape
- Surface area
- Bulk density
- **Kernel density**
- Porosity
- Coefficient of friction against different materials
- angle of repose
- Heat capacity
- Thermal conductivity
- Thermal diffusivity
- Moisture diffusivity
- Equilibrium moisture content
- Latent heat of vaporization

❖ These properties vary widely, depending on **moisture content**, **temperature**, and **density** of cereal grains.

❖ The experimental measurement of the physical and thermal properties of cereal grains is the concern of postharvest **technologists** and **researchers**

Environmental Physical Factors:

- Temperature
- Moisture content of the crop
- Relative humidity (Rh) of the atmosphere
- Concentration of atmospheric gases (oxygen, carbon dioxide)

➢ 1000-Grain Weight (1000-kernel weight)

- In **handling** and **processing** of grains, it is customary to know the weight of 1000 grain kernels
- The 1000-grain weight is a good indicator of the **grain size (**and **grain density)**, which can vary relative to **growing conditions** and **maturity**, even for the **same variety** of a given crop
- It is determined by **seed counter**
- When compared with **other crops** at **the same moisture** level, the 1000-kernel weight will also provide an idea of **relative size** of the kernel for **handling** purposes
- 1000-kernel weight increases **linearly** with increasing **moisture** content
- It is a good indicator for prediction of **milling yield** of wheat
- The **larger** the grain and the higher its **density**, the higher the ratio of endosperm to non-endosperm parts and vice versa

Seed Counter

Table 1 1000-Grain Weight, Sphericity, and Roundness of Grains

Product	Moisture content (% w.b.)	1000-grain weight (kg)	Sphericity	Roundness
Faba[fava]beans	8.5–34.9	$0.371 + 3.7 \times 10^{-3}m$	—	—
Gram	12.4–32.4	$0.156 + 1.562 \times 10^{-3}m$	0.735	0.697
			0.810[a]	0.813[a]
Malt	4.89–41.66	$0.0352 + 0.627 \times 10^{-3}m$	—	—
Oilbean seed	4.3		0.605 ± 0.277	0.398 ± 0.357
Pigeon pea	12.8	0.076	0.822	0.818
Soybean	8.0–20	$0.101 + 0.105\ m$	$0.803 + 0.06\ m$	—

[a]Without root: m, moisture content.

Density

- Density is the mass of a unit volume of a substance:

$$\underbrace{\rho}_{\text{density}} = \frac{\overbrace{m}^{\text{mass}}}{\underbrace{V}_{\text{volume}}}$$

- **Bulk solids** have been described as a kind of **fourth form of matter** between solid and liquid

- They consist of loose solid particles interspersed with **voids** (usually filled with air) and behave like a liquid, flowing to fill containers
- Grain bulks are **not homogeneous**: properties inevitably vary, sometimes considerably, throughout the bulk

- The volume of bulk solids can be defined and measured in **different ways** and this leads to different definitions of their density:
  - Bulk density
  - Specific density

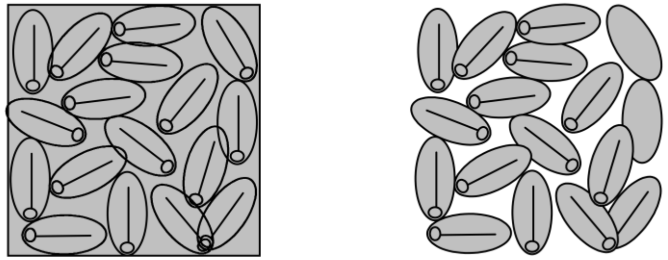


Fig. 3.2 Bulk density (left); specific density (right). Shaded area = the volume included in the calculation of density.

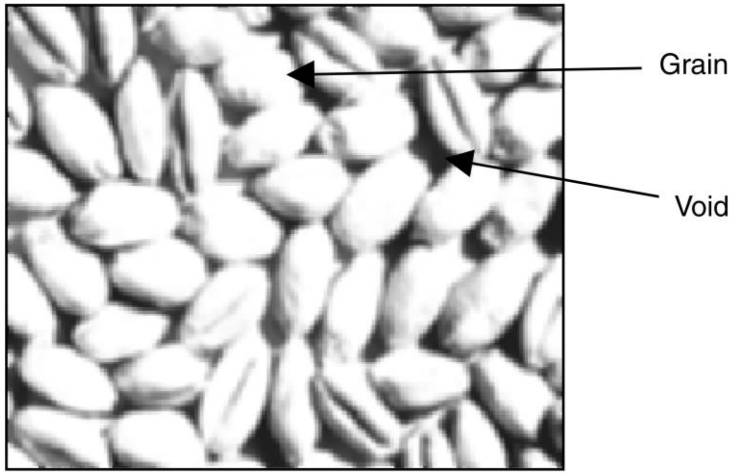


Fig. 3.1 Wheat – a bulk solid – showing solid particles (grains) and voids filled with gas (air).

Bulk density (test weight) (Hectoliter weight)

Kg/hl, Lb/bushel, Kg/m^3

- This is the **most commonly used** density measurement for stored products
- A container of known volume is filled with the bulk solid and weighed. The bulk density of the grain sample is obtained simply by dividing **the weight** of the sample by **the volume** of the container
- The volume thus includes the **solid particles**, **air** within any pores in the solids and **air** within the voids
- The bulk density of grain is used as both a **qualitative** and **quantitative** measurement:

- It is used to indicate the breadmaking potential of wheat
- To predict milling yield of wheat
- Soundness of grain
- Has an effect on the performance of continuous flow grain driers
- As a **quantitative** value it allows calculation of the capacity of existing **storage** facilities

  or the specification of storage capacity based on the mass of grain to be stored

Metric system: Kilogram/hectoliter

US & Canada: Pounds per Bushel (Lb/bushel)

US: Winchester bushel

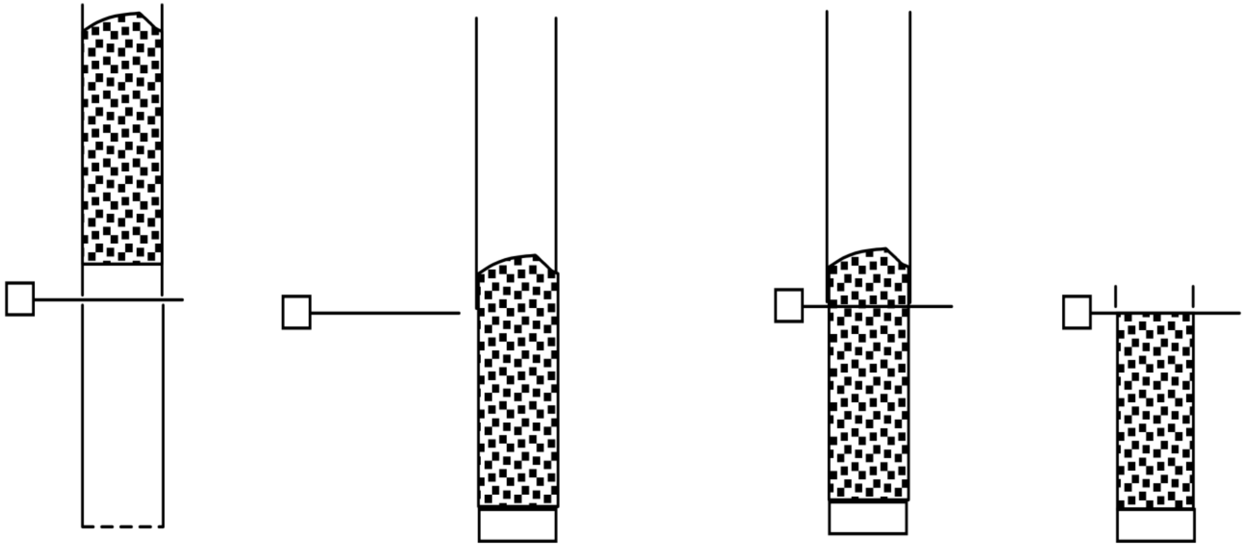
Canada: Imperial bushel

1 Bushel wheat ≈ 27/2 Kg

Conversion Factors for Wheat Test Weights

Initial System	Conversion Multiplier	Final System
Pounds per Winchester bushel	× 1.032 =	Pounds per Imperial bushel
Pounds per Imperial bushel	× 0.969 =	Pounds per Winchester bushel
Pounds per Winchester bushel	× 1.297 =	Kilograms per hectoliter
Kilograms per hectoliter	× 0.777 =	Pounds per Winchester bushel
Pounds per Imperial bushel	× 1.247 =	Kilograms per hectoliter
Kilograms per hectoliter	× 0.802 =	Pounds per Imperial bushel

Chondrometer



- **Low test weights** are found in grains that have been harvested before reaching physiological **maturity** or grains that have been invaded by **field or storage fungi**, resulting in excessive **loss in dry matter** and thus give rise to lower crop value❶

- **Bulk density is also affected by:**
  - The size homogenity and shape of the grains and their surface properties
  - The moisture content of the grains
  - The amount of impurities or foreign matter
  - kernel density and kernel packing

- The **method of storage** will affect the bulk density of the grain:
  - For example, when products are stored in **bags**, the air spaces between the bags result in a further decrease in overall bulk density
  - This reflects a **decrease in the overall quantity** of grain per unit volume and not a decrease in **the quality** of the grain

- From the **storage** point of view, it is important to determine the effect of **moisture content** on the bulk density of grains because the bulk density of **some grains increases** with an increasing moisture content, whereas it **decreases** for some other grains

- The bulk densities of **rough rice (paddy)** increases linearly with an increasing moisture content between 12 and 18%
- Whereas the bulk densities of **canola, fababeans, flaxseed, gram, lentils, malt, and soybean** decrease linearly with an increasing moisture content ❶

- Bulk density **increases** during the **drying process** to a maximum around 14–16%
- This can affect the **capacity of storage bins** – a **decrease in test weight** means that bins will hold less or must be increased in volume
- Equations **modelling** the change in test weight with moisture content exist

Table 1. Increase in test weight during drying for mature corn harvested between 18 and 28 percent kernel moisture

Harvest Moisture Content	Increase in Test Weight
%	lbs/bu
18	1.5
20	2.0
22	2.5
24	3.0
26	3.5
28	4.0

Specific, absolute or kernel or true density

- ❑ The ratio of the mass of a grain sample to the solid volume occupied by the sample

- ❑ Two methods have been suggested (pycnometer):❶

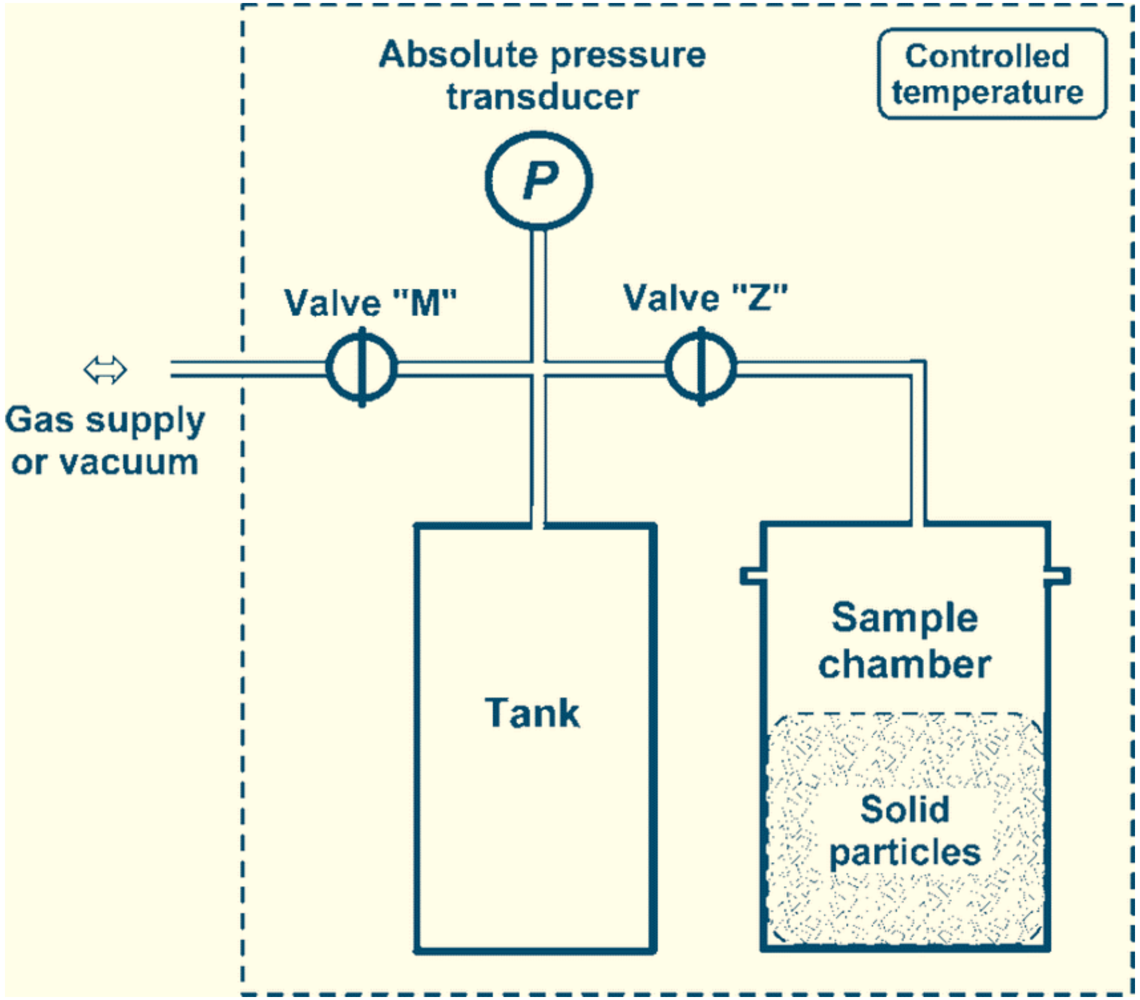
  - ✓ Displacement of a gas (helium, air)
  - ✓ Displacement of a liquid (toluene, alcohol)

- ❑ The specific density, like the bulk density, is **moisture dependent** and a mathematical model may be fitted to the data

- ❑ The kernel density varied from 1324 to 1372 kg/m3 for **medium-grain rice** and from 1362 to 1385 kg/m3 for **long-grain**

- ❑ The true densities of **bran** of long and medium rice were reported to be 1080 kg/m3, and 1000 kg/m3, respectively

- ❑ The **bulk density** of a product is lower than its **specific density** because **air** has a much lower density than the grain kernels



Gas Pycnometer

Liquid Pycnometer

$$P_1V_1 = MR_1T_1$$

$$P_2\left(V_1 + V_2\right) = MR_2T_2$$

$$R_1T_1 = R_2T_2 = RT$$

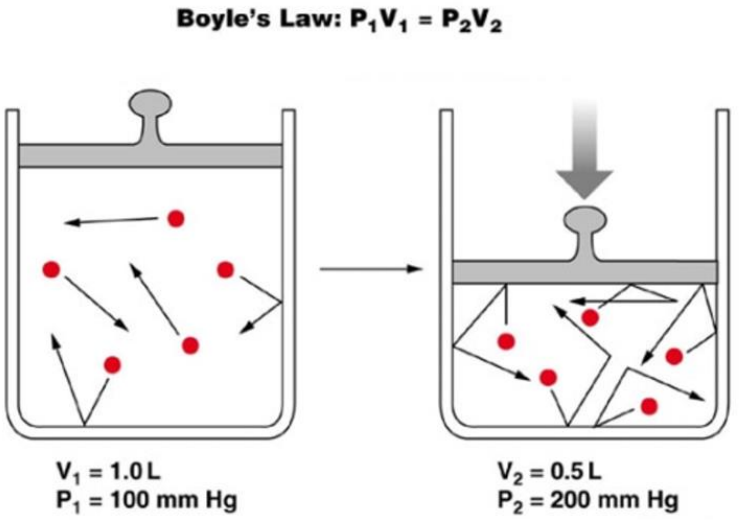
$$P_1V_1 = P_2\left(V_1 + V_2\right)$$

$$P_1V_1 = P_2V_1 + P_2V_2$$

$$P_2V_2 = \left(P_1 - P_2\right)V_1$$

$$\frac{V_2}{V_1} = \frac{P_1 - P_2}{P_2}$$

$$void\ volume = \frac{V_2}{V_1}$$



همان طور که در تصویر فوق مشخص است، در دمای ثابت با کاهش حجم ظرف از 1 لیتر به 0.5 لیتر (L)، فشار نیز از 100 میلی متر جیوه (mm Hg) به 200 میلی متر جیوه افزایش پیدا کرده است.

لذا حاصل ضرب فشار در حجم در حالت اول و دوم با هم برابر است.

Table 2 Bulk Density, Kernel Density, and Porosity of Grains

Product	Moisture content (%wb)	Bulk density (kg/m^3)	Kernel density (kg/m^3)	Porosity
Bran	13.6	235	—	—
Canola[a]	5.0–19.0	672–661	1122–1118	0.401–0.409
Canola[b]		678–661	1126–1118	0.403–0.409
Corn (BoJac)	11.8		1452 (0.53)	
Corn (Stauffer)	12.0		1450 (1.29)	
Faba[fava]beans	8.5–34.9	883–4.44 m	—	—
Faba[fava]beans	12.6–21.9	815–761	1393–1373	—
Flaxseed	7.0–15.1	634–574	1148–1143	—
Gram	8.8–23.7	814.8–3.45 m	1340–2.73 m	39.1 + 0.145 m
Lentil	6.1–24.6	1212–8.95 m	—	27.3 + 0.159 m
Lentils (Eston)	11.4–18.0	825–783	1410–1392	—
Lentils (Laird)	11.7–17.7	804–767	1431–1393	—
Malt	4.89–32.4	527–4.48 m	—	—
Oilbean seed	4.3		1120 ± 34	
Pigeon pea	12.8	782	1283	
Rice bran[b]	—	290	1080	0.73
Rice bran[d]	—	280	1000	0.72
Rice (rough)[c]	12–18	598–648	1324–1372	58.5–53.1
Rice (rough)[b]	12–18	586–615	1362–1383	59.6–56.9
Rice (short)	11.24–19.45	632–664	—	—
Rice (paddy)	8.9	639		
Rice (white)[a]	12.9	851		
Rice (white)[a]	13.3	823		
Rice (white)[d]	13.2	839		
Rice (Panoli)	10.5	780	1465	0.47
Sorghum (Ferry Morse)	12.7		1471 (0.68)	
Sorghum (Funk)	11.2		1448 (0.60)	
Soybean	8.0–20.0	748.9–166.3 m	1254.8–525.8 m	0.405–0.136 m
Wheat[a]	8.0–22.0	790–686	1374–1332	0.425–0.485
Wheat[b]		766–686	360–332	0.419–0.485
Wheat	9.1	827		
Whole meal	9.3	542		
Wheat (hard) (Newton)	13.8		1476 (0.42)	
Wheat (hard) (Centurk)	13.8		1469 (0.54)	
Wheat (soft) (Hart)	13.6		1478 (1.13)	
Wheat (soft) (Pike)	13.5		1463 (0.44)	

Table 3.1 Typical bulk densities of stored products.

Products (bulk unless otherwise stated)	Bulk density (kg/m^3)
Wheat	768–805
Wheat (bagged)	680
Barley	605–703
Oats	438–561
Rye	721
Sorghum	733
Paddy	576
Paddy (bagged)	526
Oilseed rape (canola)	689
Linseed	712
Peas	835
Beans (field)	859
Rice	579–864
Rice (bagged)	690
Maize (shelled)	718–745
Maize (shelled, bagged)	613
Millet	853
Millet (bagged)	743
Groundnuts (in shells)	352
Groundnuts (in shells, bagged)	322

Void ratio

- The ratio of the **volume of voids** between grains to the **total volume** occupied by the bulk grain is called the void ratio or **porosity**

- The void ratio can be calculated from the ratio of **bulk** to **specific** density ($V = \frac{\rho_b}{\rho_s}.100$)

- It is surprisingly **high**, ranging from 40–48% for **wheat**, maize and **rice**

- The porosity of grain depends upon:

  - ✓ Size and shape of the grains: **Flour** has a **high** void ratio (55%) because the milling process produces highly **irregularly shaped** particles
  - ✓ Their elasticity
  - ✓ Surface state
  - ✓ Dockage (non-grain foreign material) level
  - ✓ Weight
  - ✓ Compaction
  - ✓ Storage period
  - ✓ Distribution of moisture

- The **resistance** of grain to **airflow** during drying or **aeration** is partly due to the porosity of the grains and their size

- The **void volume of a grain store** (i.e. the void ratio/store volume) may be needed when calculating the concentration of fumigant or the quantity of air needed to complete an air exchange during aeration

Sphericity and Roundness

- Accurate estimation of shape-related parameters are important for determination of **terminal velocity**, **drag coefficient**

- It is important to know the **shape** before any heat or moisture transport analysis can be performed

- *Sphericity* is defined as the ratio of the **surface area** of a sphere, which has the same volume as that of the solid, to the surface area of the solid

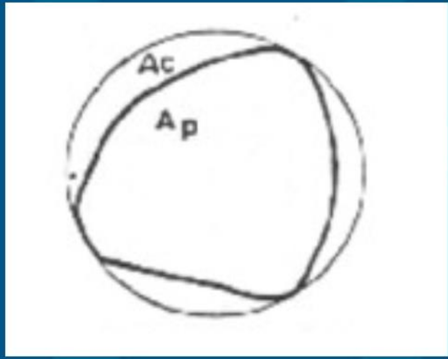
- *Roundness* of a solid is a measure of the **sharpness of its corners** and is defined as the ratio of **the largest projected area** of an object in its natural rest position to the **area of the smallest** circumscribing circle

- Higher values of sphericity and roundness indicate that the object's shape is **closer being spherical**

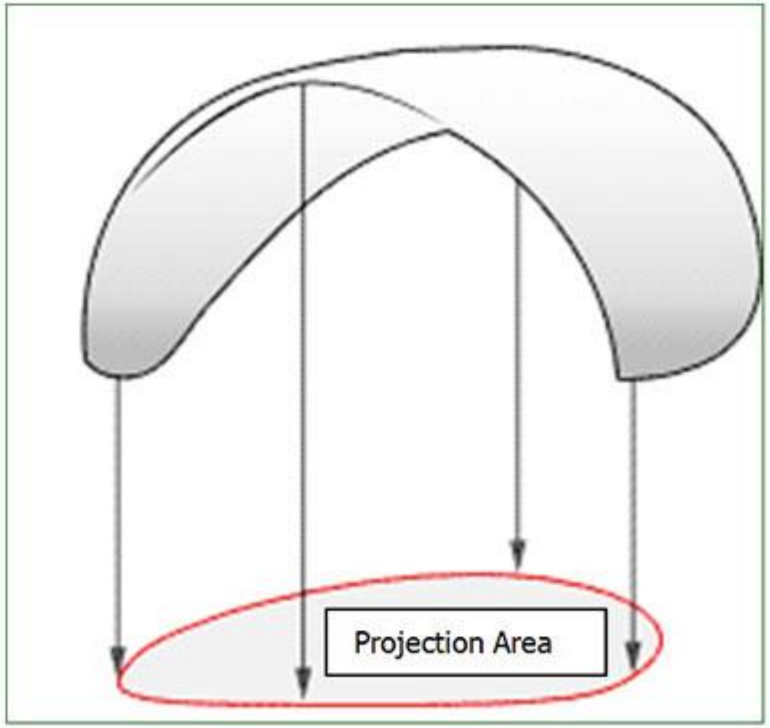
- This property could help in the design of **hoppers** and **dehulling equipment** for the seed

- Measure of sharpness of the corners of the solid

$$Roundness = \frac{A_p}{A_c}$$



- A_p = largest projected area in natural rest position
- A_c = area of smallest circumscribing circle



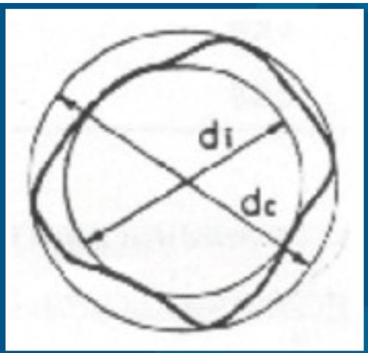
ضریب پسار (Drag Coefficient)

در علم آیرودینامیک هر جسمی که در هوا (یا سیالی دیگر) شناور باشد یا روی زمین حرکت نماید با نیروی مخالف از سوی هوا (یا سیال دیگر) مواجه می‌شود که با حرکت وسیله مقابله کرده و در برابر آن مقاومت می‌کند،

این نیرو Drag نام دارد و در زبان فارسی پسار خوانده می‌شود که بصورت ضریبی بیان می‌شود که به شکل جسم شناور یا در حال حرکت بستگی دارد.

این عدد بدون بعد است (یکا ندارد) و Drag Coefficient یا ضریب پسار خوانده می‌شود که اصولاً مقداری کمتر از یک است و هر چه کوچکتر باشد، مبین آیرودینامیک بیشتر جسم و مقاومت کمتر آن در مقابل جریان سیال است.

$$Sphericity = \frac{d_i}{d_c}$$



- d_i = diameter of the largest inscribed cir
- d_c = diameter of the smallest circumscribed circle

Table 1 1000-Grain Weight, Sphericity, and Roundness of Grains

Product	Moisture content (% w.b.)	1000-grain weight (kg)	Sphericity	Roundness
Faba[fava]beans	8.5–34.9	$0.371 + 3.7 \times 10^{-3} m$	—	—
Gram	12.4–32.4	$0.156 + 1.562 \times 10^{-3} m$	0.735	0.697
			0.810[a]	0.813[a]
Malt	4.89–41.66	$0.0352 + 0.627 \times 10^{-3} m$	—	—
Oilbean seed	4.3		0.605 ± 0.277	0.398 ± 0.357
Pigeon pea	12.8	0.076	0.822	0.818
Soybean	8.0–20	$0.101 + 0.105\ m$	$0.803 + 0.06\ m$	—

[a]Without root: *m*, moisture content.

- 95% of oilbean seeds have a roundness of **less than 0.55** and sphericity of **less than 0.75**, which explains the difficulty in getting the seeds to roll

- Sphericity and roundness of **pigeon pea** at 12.8% moisture level using 20 **shadowgraphs** have been reported as 0.822 and 0.818, respectively

- Sphericity can be calculated:

$$\text{Sphericity} = (LWT)^{0.33}/L$$

L = length, W = width, T = thickness

Coefficient of Friction

- Static and dynamic coefficients of friction of grains on metals, wood, and other materials are needed for:

  - ✓ The **design and prediction of grain motion** in harvesting and handling **equipments**

  - ✓ Determining the **pressure** of grains against bin **walls** and silos

- The static coefficients of various cereal grains have been determined relative to different structural materials

- Friction coefficient **increased linearly** with an increasing **moisture** content because of the increased **adhesion** between the seed and the material surface at higher moisture values

Table 3 Coefficient of Friction of Grains

Product	Moisture content (% wb)	Coefficient of friction: Sheet metal	Plywood	Rubber
Gram	9.95–31.9	0.348–0.489	0.384–0.559	—
	9.95–31.9		(0.409–0.582 m)[a]	
	9.95–31.9		(0.455–0.651 m)[b]	
Kidney beans (red)	10.4–15.1	0.250 + 0.0070 m	0.245 + 0.0081 m	0.266 + 0.0106 m
		0.203 + 0.0068 m	0.220 + 0.0063 m	0.239 + 0.0078 m
Faba[fava]beans (Diana)	8.5–21.6	0.32–0.38	0.28–0.46[a]	—
			0.32–0.55[b]	
Faba[fava]beans	12.6–21.9	0.29–0.36	0.28–0.37[a]	0.31–0.39[e]
		0.52–0.61[d]	0.32–0.41[b]	0.29–0.40[f]
Flaxseed	7.0–15.1	0.27–0.66	0.33–0.56[a]	0.42–0.62[e]
		0.56–0.76[d]	0.43–0.60[b]	0.44–0.63[f]
Lentils (Estons)	11.4–18.0	0.24–0.33	0.17–0.24[a]	0.32–0.41[e]
		0.45–0.49[d]	0.25–0.31[b]	0.31–0.38[f]
Lentils (Laird)	11.7–17.7	0.20–0.30	0.15–0.24[a]	0.27–0.34[c]
		0.37–0.41[d]	0.21–0.29[b]	0.26–0.33[f]
Lentil	6.1–24.6	0.307 + 0.0063 m	0.356 + 0.0051 m	0.428 + 0.0032 m
		0.253 + 0.0046 m	0.289 + 0.0043 m	0.348 + 0.0035 m
Oilbean seed	4.3	0.331 ± 0.0162	(0.374 ± 0.0122)[a]	(0.299 ± 0.0089)[c]
			(0.418 ± 0.0182)[b]	
Peanuts (unshelled)	2.50–15.2	0.306 + 0.0122 m	0.366 + 0.0085 m	0.441 + 0.0049 m
		0.272 + 0.0065 m	0.310 + 0.0057 m	0.376 + 0.0034 m
Soybean	8.00–16.5	0.291 + 0.0036 m	0.301 + 0.0054 m	0.319 + 0.0058 m
		0.256 + 0.0031 m	0.256 + 0.0044 m	0.255 + 0.0054 m

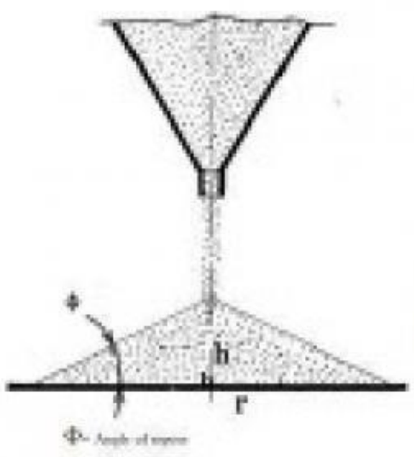
[a]Grain parallel to wood surface.
[b]Grain perpendicular to wood surface.
[c]For glass.

Angle of Repose (آرامش-استراحت)

- Natural angle between the sloping surface of a heap of grain and the flat surface on which it is placed

- Angle of repose **increases** with an increase in **moisture** content

- It can help to calculate the slope of the bottom of a silo for **discharging.** The slope angle should be more than angle of repose of the grain



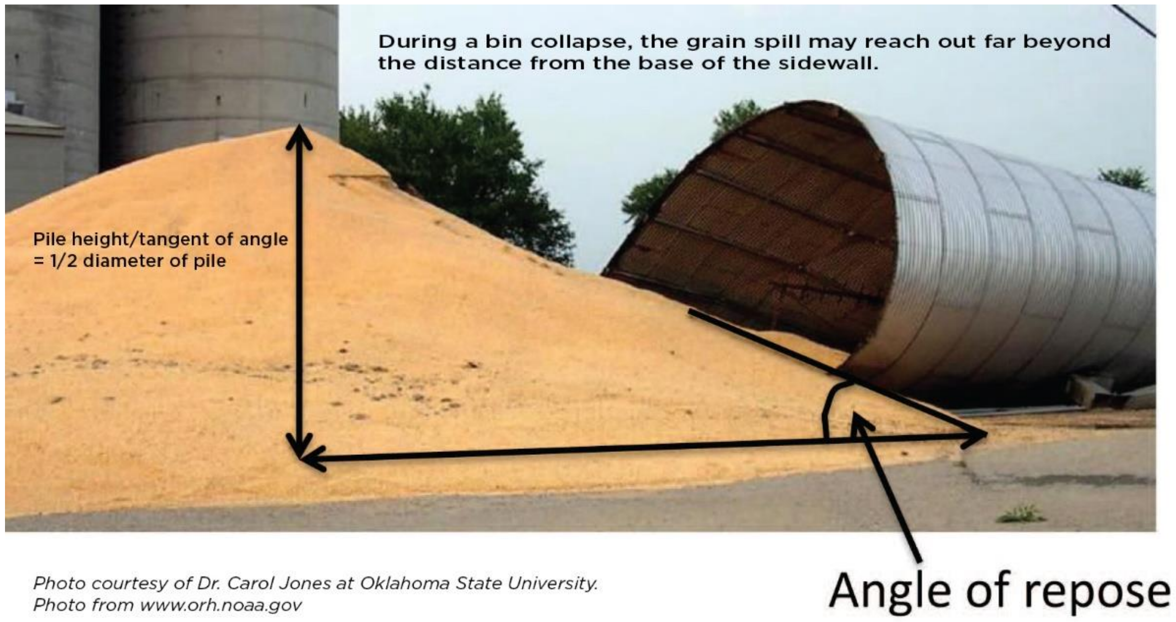


Photo courtesy of Dr. Carol Jones at Oklahoma State University.
Photo from www.orh.noaa.gov

Table 4 Angle of Repose (Emptying) of Cereal Grain

Product	Moisture (% wb)	Angle of repose degree (°)
Faba[fava]beans (Diana)	8.5–20.9	20.6–23.5
Faba[fava]beans	12.6–21.9	28.1–29.3
Flaxseed	7.0–15.1	30.3–38.0
Gram (*Cicer arietinum* L.)	12.4–32.4	$17.1 + 1.21\,m - 0.0265\,m^2$
Lentils (Eston)	11.4–18.0	25.7–28.6
Lentils (Laird)	11.7–17.7	21.6–23.9
Oilbean seed	4.3	17

Thermal properties

- **Thermal** and **moisture**-transport properties are required for simulating **heat and moisture transfer** phenomena during **drying** and **storage** of grains

- Stored products tend to be **good insulators** with **high thermal capacities**

- **Variability** in composition and physical characteristics is typical for cereal grains

- **A given grain** product may have different thermal properties, depending on its origin, concentration, and previous history

- **Thermal property values** also vary with **moisture content** and **temperature** during drying

- Most studies have reported thermal properties of cereal grains as a **function of moisture content**. Some studies have evaluated the influence of **temperature** on thermal properties of grains

✓ Hence, it is important to know the thermal property changes during drying or storage

- Apart from using thermal property data for simulating drying and storage conditions, the data are also useful in the modeling of heat treatment to wheat, corn, and legumes, as it has shown some promise in **stimulating germination**

- **Sources of heat within** stored grain bulks **(**Respiration of **insects**, mites, **micro-organisms** or the **product itself)** can lead to significant temperature rises

- **Sources of heat outside** grain bulks (e.g. daily and seasonal ambient climate), or deliberate manipulation by cooling, aeration or drying, cause **slow changes** to the grain temperature or **require a large amount of energy** to achieve rapid changes

- Therefore, The most effective way of cooling or heating stored products is to **force air** through the **voids** between the grains

- In a large silo it can take **weeks or months** for the grain to heat up or cool down (Fig. 3.4)

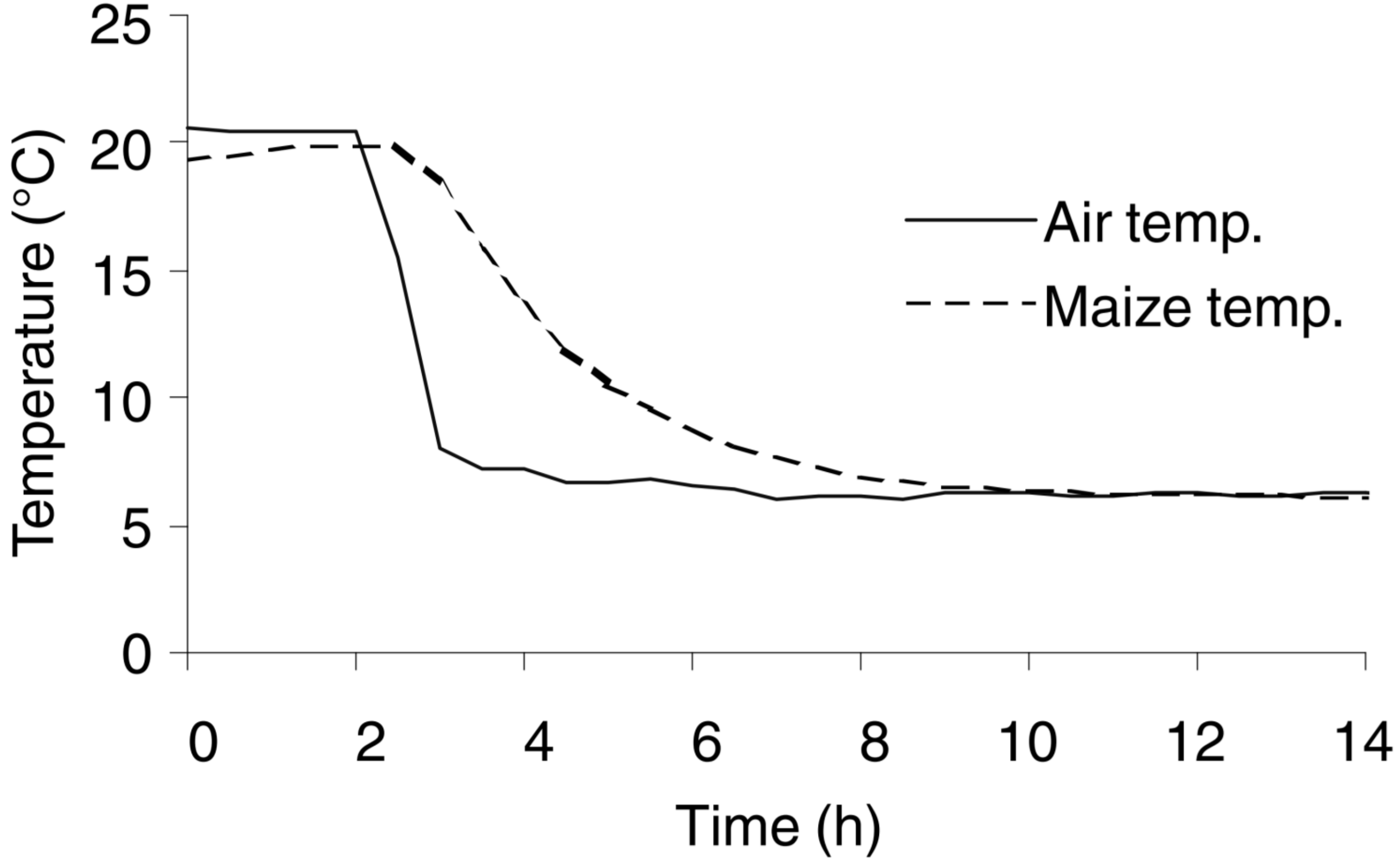


Fig. 3.4 Thermal capacity of maize and air. The graph shows what happens when a jar full of air and a jar full of maize are taken from a room at 20°C and put into a refrigerator at around 5°C. The air cools very quickly, but the maize takes nearly 10 hours to cool to the same temperature. In a large silo it can take weeks or months for the grain to heat up or cool down.

- **Heat transfer** during product storage is complex, involving **radiation**, **conduction** and **convection** processes

- There are also heat transfers due to **evaporation**, **condensation** and **adsorption**

- Thermal properties which are related to the **transfer of heat** in biological materials include:

  - dimensional characteristics
  - density
  - fluid viscosity
  - Heat transfer coefficient
  - latent heat
  - specific heat
  - **thermal conductivity**
  - thermal diffusivity

Table 3.2 Thermal conductivities of some stored products.

Product	Moisture content & temperature	Thermal conductivity (W/m K)
Wheat, maize, oats		0.13–0.18
Rice	12–20%	0.10–0.11
Sorghum	1–22.5%	0.10–0.13
Whole soybean	11.2%, 10–66ºC	0.10–0.13
Rapeseed	6.1%/4.4ºC to 12.8%/31.7ºC	0.11–0.16
Fibreglass insulation		0.035
Concrete		1.0–1.5
Iron		50

- Both **moisture content** and **temperature** have an effect on **thermal conductivity**, though the range of temperatures to which grains are exposed is limited in comparison to other materials

- Factors such as **dry matter**, chemical composition, kernel size and shape, thickness of layer, grain variety, pack density, etc. affect thermal conductivity. (reasons for discrepancies between experimental results)

- The **specific heat** (kJ/kg·K) [1] of grain is dependent on the **moisture content** and has been expressed for wheat, paddy, finished rice, soybeans, sorghum and oats etc.

- **Thermal diffusivity** and **specific heat** have also been measured using the data from **thermal conductivity** experiments

- The heat of vaporisation or **latent heat** of water in grain is the amount of energy required to **vaporize moisture** from the grain. It **falls** as the moisture content **increases** until, at high moisture contents, it approaches the latent heat of **free water**

- This means that more heat is required to vaporise water from grain at low moisture contents than from free water
- For example, 1.175 times more heat is required to vaporize water from maize at 10% moisture content than from free water at 21.1°C, while at 15% moisture content only 1.019 times more heat is required

Thermal Diffusivity

- *Thermal diffusivity indicates how fast heat can propagate through the material under transient conduction of heat-transfer conditions*

- *Physically it relates the ability of a material to conduct heat with its ability to store heat*

- *The thermal diffusivity can be calculated by dividing the thermal conductivity by the product of specific heat and mass density:*

$$\alpha = \frac{k}{(\rho C_p)}$$

α is thermal diffusivity (m^2/s)
k is thermal conductivity (W/m K)
ρ is density (kg/m^3)
C_p is specific heat (J/kg K)

- Thermal diffusivity can be determined either by **direct experiment** **or** estimated from the thermal conductivity, specific heat, and density data

Table 7 Thermal Diffusivity Data and Estimation Models of Grains

Product	Moisture (% wb)	Temperature (°C)	Thermal diffusivity (m^2/s)
Barley	10.0	10–30	9.43×10^{-8}–9.54×10^{-8}
Barley	30.0	10–30	11.0×10^{-8}–11.11×10^{-8}
Bean	0–23.1	—	8.54×10^{-8}–7.55×10^{-8}
Bean (broad)	0–23.1	—	7.98×10^{-8}–7.43×10^{-8}
Bran	13.6	30–60	1.72×10^{-7}
Corn	0–23.1	—	10.45×10^{-8}–9.23×10^{-8}
Corn	2–40	22–45	8.89×10^{-8}–8.33×10^{-8}
Corn (yellow dent)	0.9	8.7–23.3	0.001020
	5.1		0.000983
	9.8		0.000940
	14.7		0.000906
	20.1		0.000867
	24.7		0.000888
	30.2		0.000924
Faba[fava]beans (JV-2)	13.0	76.0	1.00×10^{-7}
	20.0	71.56	1.07×10^{-7}
	23.1	69.42	1.10×10^{-7}
	26.0	66.66	1.14×10^{-7}
Gram (*Cicer arietinum* L.)	12.4–32.4	10–50	$1.33E\text{-}6 - 8.45E\text{-}9\,T + 1.40E\text{-}11\,T^2 + 3.79E\text{-}8\,m - 3.83\,m^2 - 1.13E\text{-}10\,mT$
Oat	10.0	10–30	10×10^{-8}–10.15×10^{-8}
Oat	30.0	10–30	10.9×10^{-8}–11.0×10^{-8}
Pea	10.0–30.0	—	7.93×10^{-8}–6.82×10^{-8}
Rice bran (long, Lamont)	—	—	1.33×10^{-7}
Rice bran (short, Nato)	—	—	1.36×10^{-7}
Rice (paddy)	8.9	30–60	1.07×10^{-7}
Rice (paddy, medium-grain)	12–20	Room temp	0.00135 + 2.49e-5 M
Rice (rough, short-grain)	11–24	Room temp	0.00125 − 1.63e − 5 m
Rice (panoli)	10.5	—	8.65×10^{-8}
Rice (white[a])	12.9	30–60	1.00×10^{-7}
Rice (white[a])	13.3	30–60	1.00×10^{-7}
Rice (white[a])	13.2	30–60	1.01×10^{-7}
Sorghum	2–29.0	4–24	9.29×10^{-8}–8.2×10^{-8}
Soybean	8.0–40.0	20–50	4.5×10^{-8}–7.7×10^{-8}
Whole meal	9.3	30–60	1.02×10^{-7}
Wheat	10.0	10–30	9.07×10^{-8}–9.18×10^{-8}
	30.0	10–30	10.4×10^{-8}–10.5×10^{-8}
Wheat (soft white)	0.7	9.1–23.2	0.000927
	5.5		0.000896
	10.3		0.000854
	14.4		0.000801
	20.3		0.000800
Wheat	9.1	30–60	0.91×10^{-7}

Moisture diffusivity

- Moisture movement within grain masses, like temperature movement, is a **very slow process**

- Diffusion of water **within and between** grains affects:

    - **Drying rate**
    - **The rate and pattern of moisture change or migration during storage** ❶

Moisture capacity

- Although durable stored products such as cereal grains are far drier than more perishable commodities they still contain significant amounts of water

- Cereal grains typically contain 10% to 15% of water by weight during storage

- Air also contains moisture and is the medium through which moisture changes in the grain often occur

- The moisture-holding capacity of air is many times lower than grain:
  under typical conditions 1 m^3 of grain will contain 75–110 kg of water, while a similar volume of air can typically contain a maximum of 15–20 g of water, some 5000 times lower than the capacity of the grain

- Then, **large volumes of air** are required to **alter the moisture** content of stored products significantly

Fig. 3.5

Moisture capacity of maize and air.

The picture shows a 25 kg sack of maize. It will typically contain 3 litres of water, shown on the right of the photograph. If the sack contained only air, the air would typically contain around 0.4 ml of water, shown in the tiny flask on the left of the photograph

Environmental Physical Factors (slide 48):

Temperature

- Temperature affects the **rate of all biochemical processes** and is therefore of fundamental importance in any storage system

- Together with **moisture** content, it largely determines the **storage life** of grain

- The temperature of the **(1)** stored product and that of the **(2)** air around and within it are both important

- Insects, mites[1], fungal and mycotoxin development, germination loss and baking qualities are affected by temperature

- At temperatures found in grain stores, **biological activity** of insects, mites, fungi and the grain itself **doubles** for every **10°C** rise in temperature

Effect of different temperatures on the risk of insect and mite infestation

Risk	ºC	Effects on insects	Effects on mites
Least	60	Death in minutes	Death in minutes
		Death in hours	Death in hours
	50		
		Development stops	Death in days
	40	Development slows	
	30	Maximum development rate	No increase
Greatest		Development slows	Maximum development rate
	20		
		Development stops but all stages survive	Development slows
	10		
		Movement stops, death in months	
	0	Lowest development rate	
		(Fungi can still grow in damp grain)	
	–10	Death in weeks	Death in weeks
Least			
	–20	Death in minutes, insects freeze	Death in minutes, mites freeze

- At **low temperatures** insect breeding stops and **less moisture is available** for potential pests in cold grain

- Therefore, grain should be **cooled immediately** after drying and before it comes into store

- **Cooling** during storage will also **equalize temperature** gradients and so prevent moisture translocation ❶

- A temperature rise on the **outside of a grain bulk** causes a heat front to move through the grain at a rate of approximately **2 metres per month**

- In a **bag stack** the heat front moves at approximately 4 metres per month

- This typically occurs in **tropical and subtropical climates** at the onset of a season when the average ambient temperature rises

Moisture content

- Many stored products are **hygroscopic** materials, so that they can absorb and release water, rather like a sponge

- In other words, they consist of an amount of **dry matter** and an amount of **water**

- The **moisture content** (m.c.) expresses the **weight of water** in a product as a proportion of its weight

- The most common method of expression is known as the **wet basis**, shown in **Equation 3.1**

- In scientific work the **dry basis**, shown in **Equation 3.2**, may be preferred

$$\text{m.c. (wet basis)} = \frac{\text{weight of water in sample}}{\text{wet sample weight, i.e. weight of water + dry matter}} \times 100\% \quad (3.1)$$

$$\text{m.c. (dry basis)} = \frac{\text{weight of water in sample}}{\text{dry sample weight, i.e. weight of dry matter}} \times 100\% \quad (3.2)$$

$$M_w(\text{wet basis}) = \frac{w - d}{w} \times 100$$

$$M_d(\text{dry basis}) = \frac{w - d}{d} \times 100$$

w: total weight

- **Dry basis moisture** is most commonly used for describing moisture changes **during drying**
- When a sample **loses or gains** moisture, the change in the **dry basis moisture** is linearly related to the weight loss or gain

- Equations 3.3 and 3.4 can be used to **convert between wet basis and dry basis** moisture contents:

$$\text{m.c. (wet basis)} = \frac{100 \times \text{m.c. (dry basis)}}{100 + \text{m.c.(dry basis)}} \qquad (3.3)$$

$$\text{m.c. (dry basis)} = \frac{100 \times \text{m.c. (wet basis)}}{100 - \text{m.c.(wet basis)}} \qquad (3.4)$$

- When presenting moisture contents the **basis used should be stated**, e.g. 15% (wet basis) or 15% (w.b.)
- Moisture content is fundamentally important in establishing safe storage conditions

- Changes in moisture content also cause a **change in the overall weight** of a commodity, and as products are often **traded by weight** this has obvious **financial implications**

- The change in weight of a commodity when its moisture content changes can be calculated from **Equation 3.5:**

$$\text{Final weight} = \text{Initial weight}\left(\frac{100-a}{100-b}\right) \tag{3.5}$$

a = the initial moisture content
b = final moisture content

For example, if 1000 t of wheat is dried from 17% to 15% m.c. (w.b.) its final weight will be:

$$\text{Final weight} = 1000\left(\frac{100-17}{100-15}\right) = 976.5 \text{ t}$$

Relative humidity

- Air is a mixture of gases. One of the gases it contains is water vapour, that is, water in its gaseous form.
- Each constituent of a gas mixture exerts a pressure, called its **partial pressure**, in proportion to its volume
- The **sum of the partial pressures** for each constituent of a gas mixture equals the **total pressure** exerted by the mixture ❶
- The **term humidity** refers to the proportion of water vapour in the air

- **Three primary measurements of humidity are: absolute**, **relative** and **specific**.

1. Absolute humidity is the mass of water in a certain volume of air and is expressed in either **g** per **m³**
2. **Specific humidity** (or moisture content) is the ratio of the mass of water vapor to the total mass of the moist air (g/Kg)
3. Relative humidity, expressed as a percentage, indicates a present state of absolute humidity relative to a maximum humidity given the same temperature (the amount of water vapour that is in the air as a proportion of the amount of water vapour required to saturate the air at the same temperature)

$$r.h. = \left(\frac{p_w}{p_{ws}}\right) \times 100$$

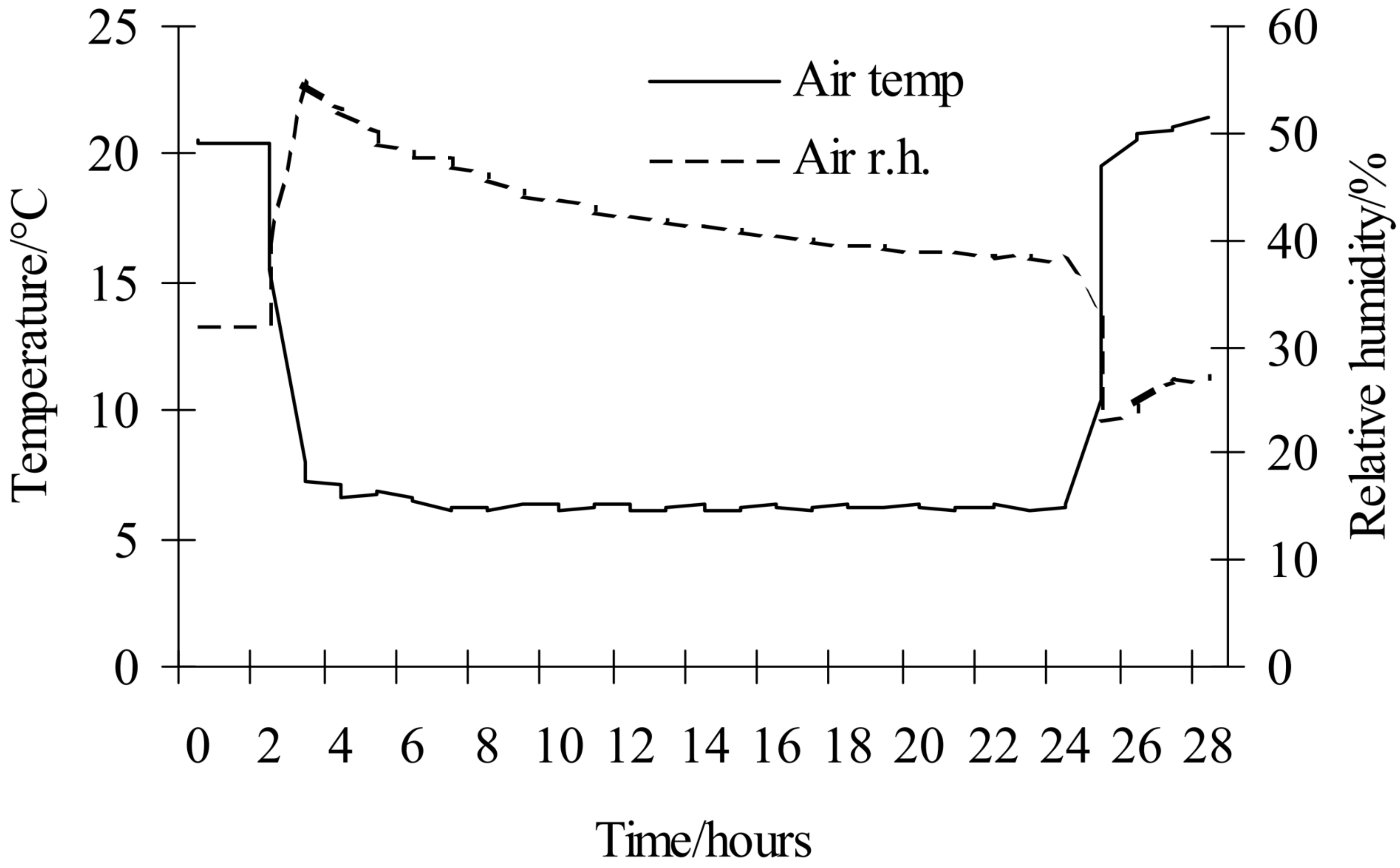


Fig 3.6. Relative humidity within a jar of maize rises when the jar is placed into a refrigerator

- **Relative humidity** is more **useful** than absolute measures of humidity for determining the response of living things or biological materials to the air around them

- **For example**, the ability of the air to **dry water from crops** or sweat from our skin depends on the degree to which it is saturated i.e. on its **relative humidity**

- Most importantly, in **food storage** the relative humidity of air around the product is one of the most important factors controlling spoilage by micro-organisms

- **Water vapour in the air around a stored product interacts with the water held in the product,** so when stored products are present, the relative humidity depends **not only** on the partial **pressure of the water** and **temperature** but also on the moisture content of the stored product **(Fig 3.7)**

- Because **air temperatures** vary throughout the **day** and **night** the relative humidity of the air will also vary, often by a large amount, as shown in **Fig. 3.8**

- This is important when ambient air is used to **aerate or ventilate** stored grains

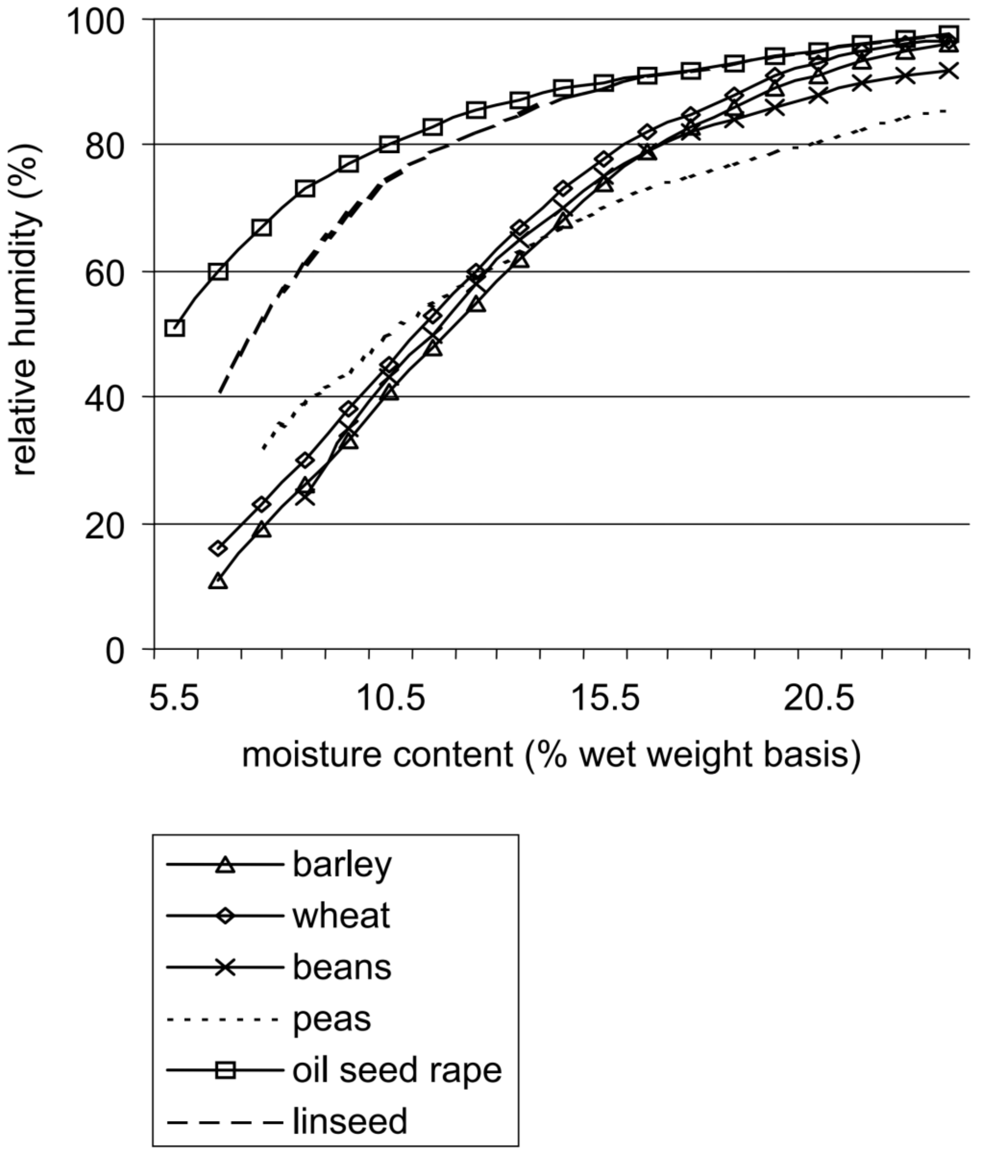


Fig. 3.7 The relationship between relative humidity and moisture content in some stored commodities. Source:

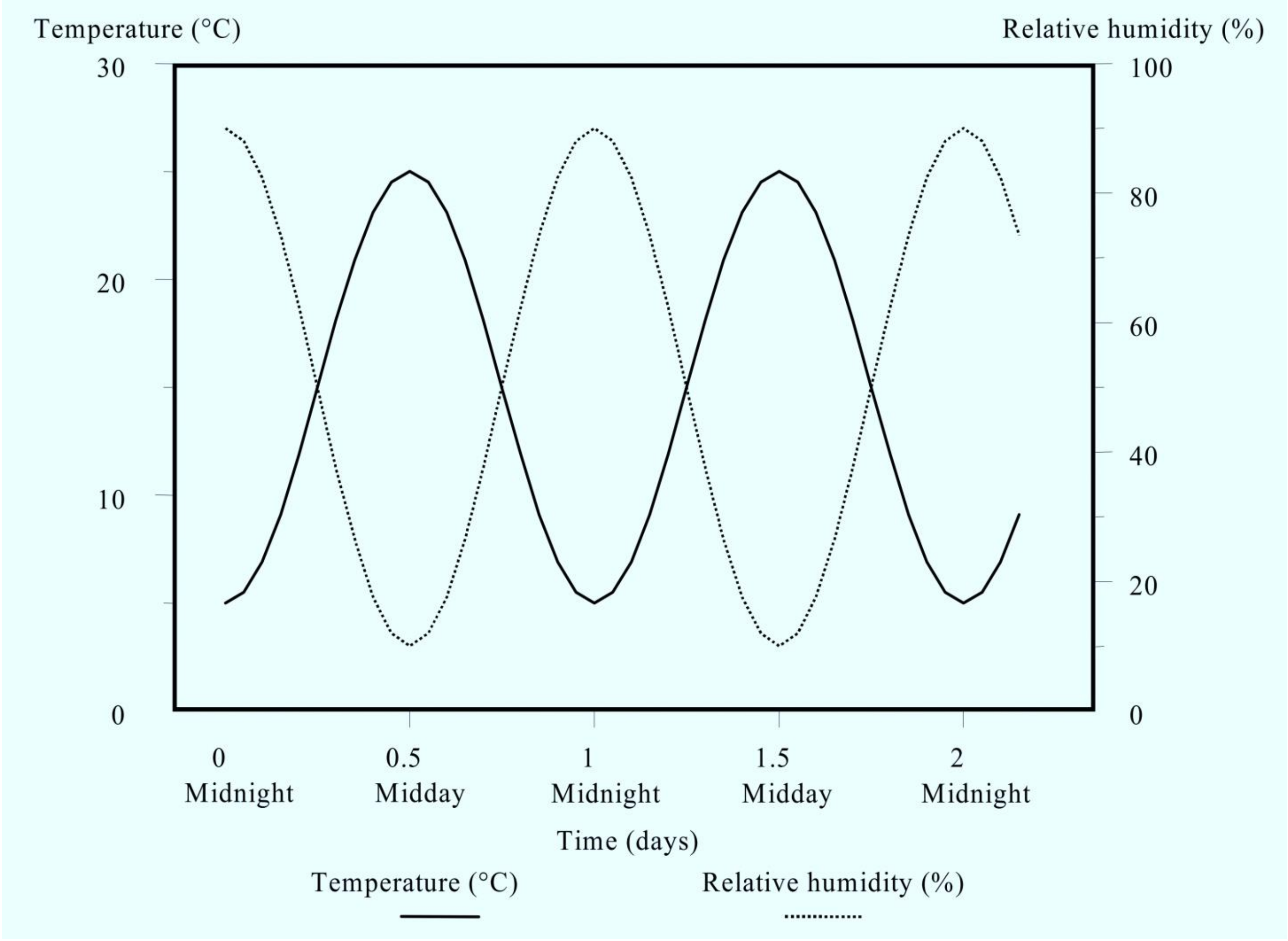


Fig. 3.8 Fluctuations in temperature and relative humidity over 24 hours

Water Vapour Condensation

- **Hazards** occur when the **temperature falls** at night and the **relative humidity** of the air rises

- If the **temperature falls** by a large enough amount the relative humidity of the air can rise to **100%** and liquid water will begin to **condense** out

- **Therefore**, It is clearly **undesirable** to bring air in this condition into contact with a stored grain

- *Problems can also occur within **storage buildings or structures***

- The **roof** of a warehouse can get **very cold at night** while **air** rising from stored produce (a bag stack of grain) may be relatively **warm and moist**

- The air will cool and can reach **saturation** in contact with the cold roof
- **Condensation** will then occur on the underside of the roof, causing water to drip on to the bag stack below and form a wet layer which will spoil due to mould growth **(Fig.3.9.)** ❶

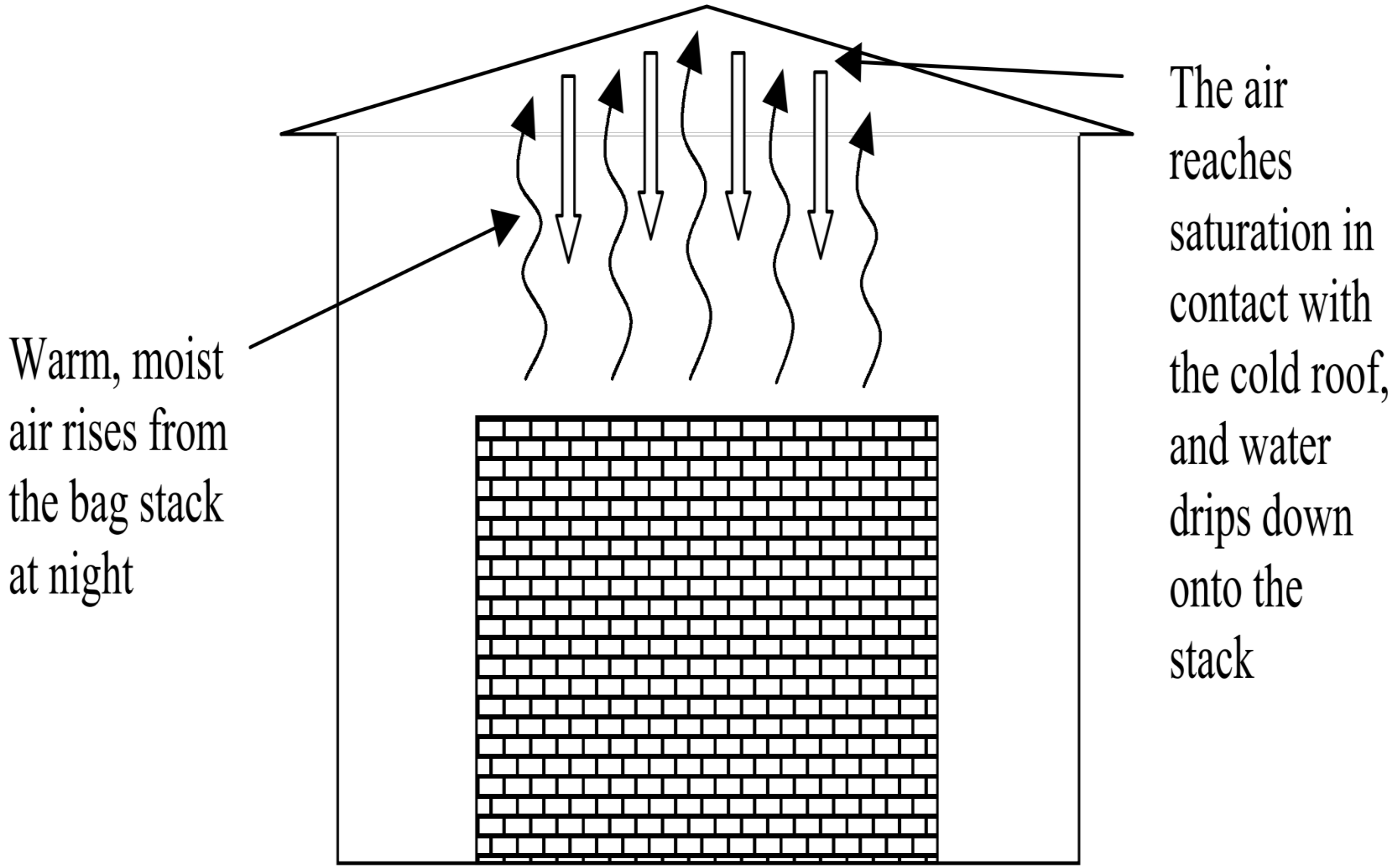


Fig. 3.9 Night-time condensation, or raining, in a warehouse. The same phenomenon may occur inside shipping containers when they arrive in a cold climate from a hot one (internal raining).