4. DRYING of GRAIN in BULK
(using near-ambient method)

4.1. INTRODUCTION

Question 4.1. Is it possible to dry grain in bulk several meters thick once it has been stored in a silo or on-floor store?

The theoretical bases of drying grain in bulk were elaborated in Poland in the 1950s by Stanisław Pabis but serious interest in this method of grain preservation increased in the USA, Canada and the UK after the world fuel crisis at the beginning of 1970s. (Other terms used to describe the same method are: 'low-temperature drying', 'bulk storage drying', 'drying at the temperature close to the surrounding air' or 'near-equilibrium drying'.) This method of drying involves forced ventilation, by a fan, of a deep, stationary bed of grain. Generally speaking, the method utilizes the drying potential of the atmospheric air and the ventilating air is heated only in exceptional conditions when the drying potential is lacking, but even then the air is heated up only by a few degrees Celsius. The energy necessary to evaporate 1 kg of water from the grain bulk, is much smaller in comparison with other methods of drying (Figure 4.1).

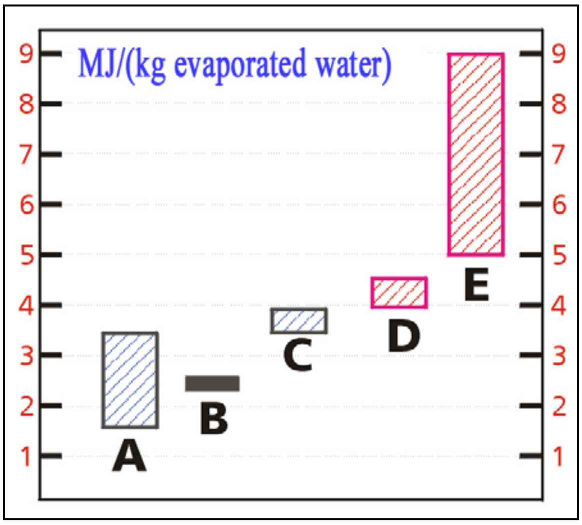

Figure 4.1. Energy consumption to evaporate 1 kg of water from grain bulk (so-called specific energy consumption) using different methods of drying: A – near-ambient drying with non-heated air – depending on weather conditions - ranges from 1.5 to 3.5 megajoules per 1 kg of evaporated water [MJ/(kg evaporated water)]; B – heat of evaporation of water (quoted for the sake of comparison); C – near-ambient drying in silos with radial air flow; D – high-temperature drying in mixed-flow driers; E - high-temperature drying in driers with cross flows – the best ones use about 5 and the worst ones – about 9 [MJ/(kg evaporated water)] (McLean 1989).

Some of the reasons why near-ambient drying is so popular include:

a) low costs of equipment and their operation,
b) low involvement of the workforce to service the equipment,
c) elimination of transport to and from the drying plant (e.g. in the case the farmer has not got a high-temperature dryer),
d) good quality of the dried grain if the risk of contamination by moulds is eliminated.

In the humid maritime climate of Great Britain, about 50% of the harvested grain is dried by this method, typically in on-floor systems in bulks of up to 4 meters deep. In the case of the dry and cool climate of the North American prairies approximately 80% of grain is preserved using this method.

There are certain principles that need to be observed when using the method of near-ambient grain drying (e.g. the required quantities of drying air and allowable thicknesses of the grain layers for specified initial grain moisture content values). Another important factor is the appropriate control of the incoming air preventing the development of moulds. The above-mentioned principles are discussed in detail in answers to further questions.

4.2. PRINCIPLE OF NEAR-AMBIENT DRYING

Question 4.2. What is the simple explanation of the near-ambient drying process? How is it possible for air to dry grain bulk several meters thick?

Air capable of absorbing water vapor is blown by a fan into a deep bed of grain, usually from the bottom through the floor. The most advantageous arrangement for ventilation is when the floor is perforated on its entire surface. As a result of the pressure produced by the fan, the air overcomes the resistance of the grain layer and flows through inter-granular spaces. The moisture present in individual kernels is absorbed by the flowing air and taken away from the grain bulk and out the storage building by the ventilation openings in the roof. This could be the simple answer to the above question. However, it is not completely satisfactory. Another question is: **What is the driving force of the process of absorbing moisture from the surface of each kernel by the flowing air?** It is the question about process of evaporation of water from the biological materials being dried. Water evaporation is forced by the difference of pressures exerted by the water vapor molecules on the kernel surface and in the drying air. The vapor pressure (P_v, see Chapter 2) on the kernel surface must be higher than the vapor pressure in the drying air. The same positive driving force for evaporation occurs when the relative humidity (RH) of the air in spaces between kernels is lower than the air equilibrium relative humidity (ERH). An example of such situation is shown in Figure 4.2. Both terms, RH and ERH were explained in the Chapter 2, "Risk of wetting grain in bulk".

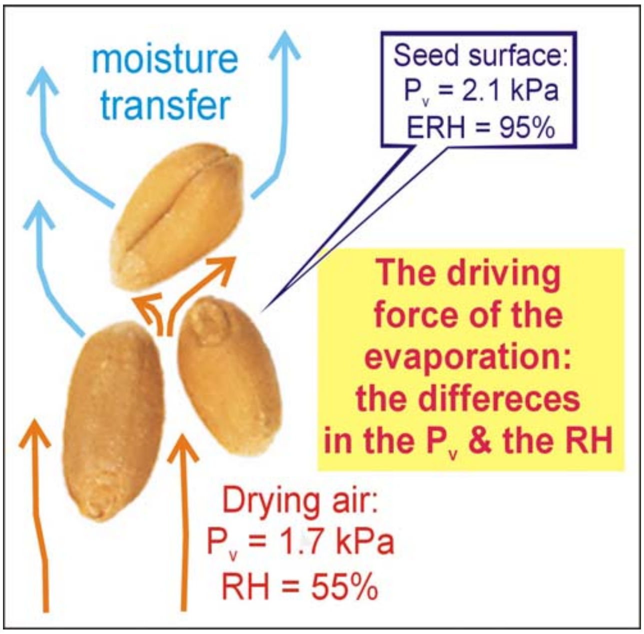

Figure 4.2. Example of the driving force of the process of evaporation of water from wheat kernel in inter-granular spaces: the differences in the P_v – vapor pressure and the RH - relative humidity of air**;** in the example drying air of temperature 25 °C and RH of 55% flows through spaces between wheat kernels of the moisture content of 20% w.b.; the temperature on the wheat surface is equal to 19.2 °C (it is the temperature closed to the temperature of moist air indicated by a thermometer whose bulb is covered with a wet wick, so-called pseudo wet-bulb temperature (Brooker et al. 1974, Nellist 1997)).

Water evaporation from the kernel surface is accompanied by the equalization of the moisture content inside it – moisture migrates from inside kernels towards the surface. Kernels are porous bodies so the rate of moisture equalization inside a kernel depends, among other factors, on its size – the bigger the kernel, the slower the equalization process. However, this is not important in near-ambient drying but it gains in significance during rapid, high-temperature drying. During evaporation, the grain decreases its moisture content and the air accumulates water vapor. It should be emphasized here that water evaporation is accompanied by heat consumption which results in the decrease of temperature of both the air and grain. The more intense the evaporation process, the stronger the temperature decrease. This is how the flow of moisture between individual kernels and air molecules can be described. Another question arises then, namely: **What is the process like in the entire grain bulk? In other words, how does the transfer of moisture from kernels to the air proceed in time in different places in the grain bulk?**

The typical process of near-ambient drying in a thick, stationary grain bed is shown in Figure 4.3. Moisture transfers from kernels to the air in those areas where the air relative humidity is lower than the equilibrium humidity. This occurs only in a relatively thin layer of grain, referred to as the ‘drying zone’ or ‘drying front’. The drying zone moves slowly in the same direction as the air flow (most frequently from the bottom upwards). Figure 4.3 shows the drying zone half way through the grain layer which means approximately half way through the period of drying.

In Figure 4.3 the air molecules are illustrated in the same way as in the Chapter 2, “Risk of wetting grain in bulk” when explaining the notions associated with the air relative humidity – dry air molecules carry containers for water vapor. The amount of water associated with each air molecule increases as the air passes through the drying zone. It can be imagined that the amount of water increases in the container for water vapor. When the air temperature drops, the container gets smaller. (This was explained in the Chapter 2, “Risk of wetting grain in bulk”). These two factors cause the fullness of the water vapor container to increase, i.e. air relative humidity increases.

When the air relative humidity increases to the level of the equilibrium humidity, moisture no longer flows from kernels to the air. This situation occurs in the grain layers above the drying zone. This means that the grain moisture content in layers above the drying zone remains on the level similar to the initial moisture content (on the day of filling the silo) almost throughout the drying period. The process of near-ambient drying takes from several days in dry years to approximately 2 – 3 weeks in wet years.

The grain moisture content in layers below the drying zone stabilizes at the level of the equilibrium humidity in relation to the humidity of the air blown in. The approximate grain moisture content which establishes after a sufficiently long period of ventilation is presented in Table 4.1 for the air with relative humidity ranging from 40 to 90%.

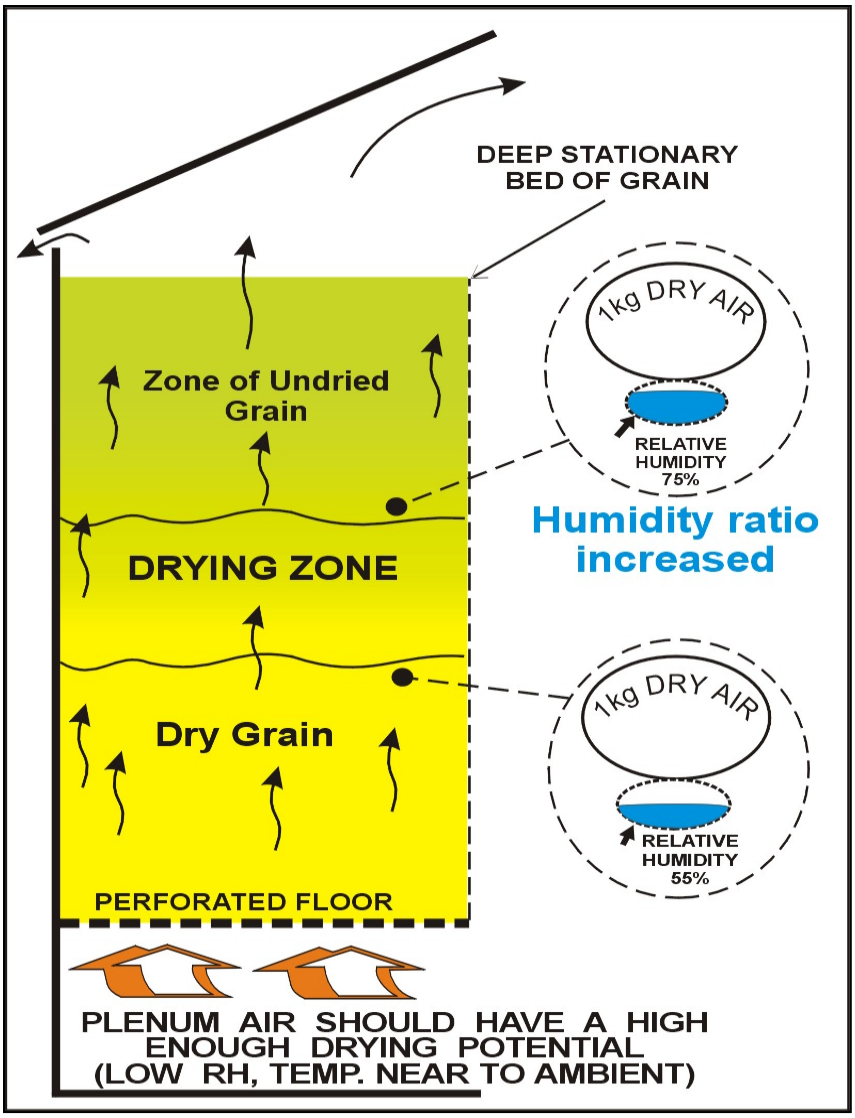

Figure 4.3. The concept of near-ambient drying, i.e. drying of a stationary deep bed of grain by way of forced, mechanical ventilation with air at a temperature close to that of the surroundings. The drying zone moves slowly in the same direction as the flow of the air. The presented values of the air relative humidity of 55 and 75% although typical, are only example values.

A question arises then: **If part of the grain remains wet for such a long period of time, will it not get mouldy**? Yes, in layers where the grain is wet, there are favorable conditions for the development of all kinds of living organisms, including mould fungi which are the most dangerous. This is, undoubtedly, a serious shortcoming of near-ambient drying and all necessary precautions must be undertaken. The problem is, at least, partially reduced by the phenomenon of natural cooling and drying of kernel surfaces in the wet grain layers in the situation when they are ventilated properly employing minimum quantities of heat. Nevertheless, it must be remembered that near-ambient drying is a race against mould development.

It is essential to dry all grain layers before mould fungi develop. In other words, it is necessary to take into account the time for which the grain will remain free of moulds at a given grain moisture content and temperature. **The keys to the success in the race against moulds include:**

a) the appropriate flow (quantity) of air penetrating all areas of the grain bulk (the bigger the flow, the better),

b) the appropriate air relative humidity and temperature (the lower, the better),

c) the appropriate control of the process.

Table 4.1. Equilibrium Moisture Content (EMC) of cereal grain and oilseed rape. EMC was calculated from Chung-Pfost equation (barley) and Modified-Halsey equation (rapeseed) using ASAE Standards 2000.

Air relative humidity (**RH**)	**EMC** - seeds moisture content (**% w.b.**) established after a sufficiently long period of ventilation with air of relative humidity according to the left column				
%	**Barley***		**Rapeseed**		
	25 °C	10 °C	25 °C	10 °C	(15 °C)**
40	10.7%	11.1%	5.6%	6.1%	5.1%
50	11.6	12.5	6.5	7.0	5.9
60	13.2	14.1	7.5	8.1	7.0
65	14.1	14.9	8.2	8.8	7.7
70	15.0	15.8	9.0	9.7	8.5
80	17.2	18.0	11.3	12.1	11.0
90	20.1	21.3	16.0	17.1	16.1

* For **wheat**, values by approximately 0.8% w.b. lower (Nellist 1997 & 1998).

** According to Modified-Halsey equation with coefficients derived by Nellist & Bruce (1992).

The parameters of the air supplied to the grain bed by the fan should be controlled in such a way as not to allow unnecessary wetting of the grain and to make the drying zone reach the layers with the highest moisture content before moulds can develop there. At the same time, it is required that the grain layers at the inlet of the drying air should not be excessively dry at the end of the drying process. This requirement usually refers to the grain which is being sold. These tasks require appropriate equipment and practice for near-ambient drying.

4.3. EQUIPMENT

<u>Question 4.3.</u> What kind of equipment should a silo or on-floor storage be equipped with for near-ambient grain drying?

The equipment required for near-ambient drying is similar to that which is employed to ventilate dry grain, described earlier. However, the job it must do differs significantly from that in dry grain ventilation and requires additional discussion. The main pieces of equipment include:

1) Perforated floor or ducts, or other device which supplies compressed air from the fan to the grain bulk.
2) Fan.
3) Air heater.
4) Measuring-control device (MCD).

A set of equipment for the process of near-ambient drying is presented in Figures 4.4 and 4.5.

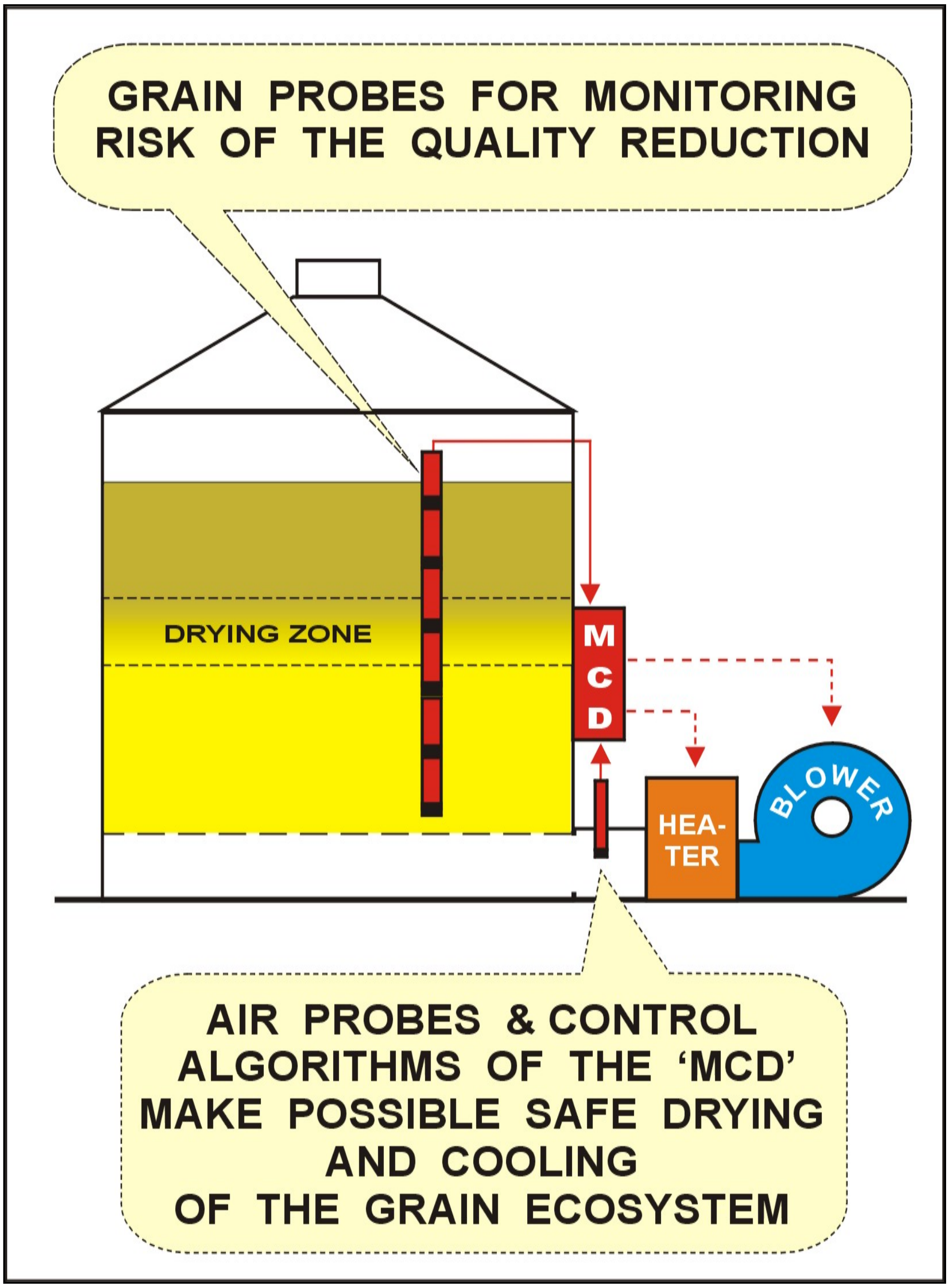

Figure 4.4. Set of equipment for near-ambient grain drying in a thick, stationary bed using air of the temperature close to that of the surrounding air; MCD refers to a Measuring-Control Device.

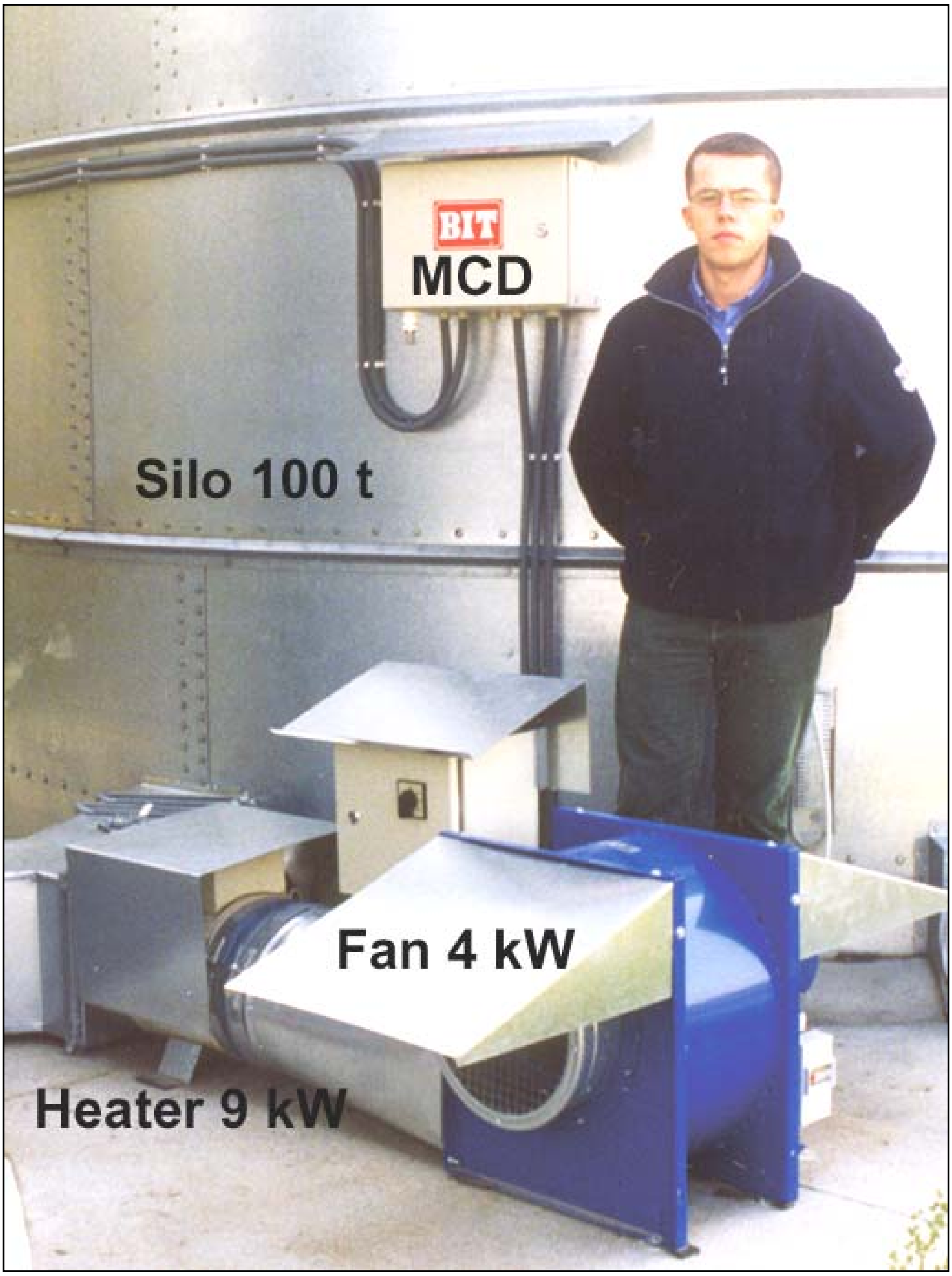

Figure 4.5. Set of equipment for the near-ambient drying of grain - example (courtesy the ‘Grześkowiak’ company, Poland).

PERFORATED FLOOR

A perforated floor is the most common device which allows the supply of compressed air from the fan to the grain bulk. It is recommended that, for the process of near-ambient drying, the floor should be perforated over its entire surface. Attempts should be made to assure the same flow of air through the entire grain bulk. This problem was discussed earlier in the previous Chapter.

FAN

(We assume that the reader is familiar with the point “Fan” in the previous chapter). The fan or blower for near-ambient drying must provide 10 – 20 times greater quantity of air in comparison with the amount required for dry grain ventilation.

The recommended air quantities vary considerably depending on the climate of the country. Manuals for British farmers, for drying grain in a maritime climate, recommend fans which can provide approximately 180 cubic meters of air per hour for each tonne of dried grain, symbol: [$m^3/(h·t)$]. This refers to the drying of grain of basic cereals from the initial moisture content of 20% w.b. in a layer up to 3 m.

A manual for Canadian farmers who dry grain in a climate with a considerably higher drying potential of atmospheric air recommends significantly smaller quantities of air ranging from 30 to 80 $m^3/(h·t)$, depending on the date of the harvest and the intended usage of the grain (Friesen and Huminicki 1987). Seed grain, for example, requires about 35% higher amounts of air.

In most European countries, values of the drying potentials of the atmospheric air are intermediate between those of the wet maritime and dry continental climates (Ryniecki et al. 1993, Ryniecki et al. 2005). This influences the air quantities required for near-ambient grain drying. According to the results of research carried out by the author, the following conditions should be provided to ensure safe drying for the climate that is the mixture of maritime and continental climates:

1) The velocity of the air flowing through the grain bulk should be about 0.07 m/s. It is approximately an average value between air flows recommended in maritime and continental climatic conditions (Table 4.2).
2) The air relative humidity (RH) should be lower than the equilibrium relative humidity (ERH). The ERH should be calculated using the following information: a) type of the raw material being dried, b) its temperature measured on-line, c) the maximum moisture content for safe storage (e.g. 14.5% w.b. for cereal grains, 7.5% w.b. for rapeseed). The difference ERH-RH can vary in the range 0 ÷ 10%; for most of the drying time should

vary in the range 5 - 10%, but for short periods of time, e.g. several hours during unfavorable weather conditions, can vary in the range 0 ÷ 5%.

3) the thickness of the grain layer and the recommended quantities of air, which depend on the grain moisture content at initiation of drying, should not exceed values given in Table 4.3.

Table 4.2. Influence of climatic conditions on the recommended **air flows** that must be provided by a fan to the bed of grain being dried in bulk.

Climate	Moisture content / bed depth	Air velocity [d]	Specific airflow [e]
	% w.b./ m	m/s	$m^3/(h \cdot t)$
Maritime [a]	20 / 3	0.11	180
Continental [b]	20 / 3	0.04	55
A mixture of maritime and continental [c]	20 / 3	0.07	111

a) in the south and east of the UK (higher air flows in the west & north of the UK) – McLean 1989 and personal communication at Silsoe Research Institute;
b) in Canadian prairies – average air flow based on Friesen and Huminicki 1987;
c) in Poland - based on research carried out by the author of the handbook;
d) apparent air velocity (measured by an anemometer);
e) specific airflow converted into wheat grain of 0.76 t/m^3 density.

Table 4.3. Acceptable depths of the grain bed and associated airflow rates for given initial moisture contents of grain from the point of view of retention the grain initial quality, helpful to design a drying system. Investigations were conducted on the basis of weather conditions in the climate that is the mixture of continental and maritime climates (in Poland). Grain quality was monitored using the criterion of the degree of mould development.

Grain moisture content	Bed depth	Air velocity[a]	Air volume flow per 1 m^2 of floor area that must be provided by a fan[b]	Specific airflow[c]
% w.b.	m	m/s	m^3/s	$m^3/(h \cdot t)$
17	6	0.07	0.07	55
20	3	0.07	0.07	111
22	1	0.07	0.07	332

a) apparent air velocity (measured by an anemometer);
b) this air volume flow must be provided by a fan to each square meter of the cross-section of the bed of grain;
c) specific airflow converted into wheat grain of 0.76 t/m^3 density.

AIR HEATER

The ventilating air should be heated only in exceptional conditions when the drying potential of ambient air is lacking, but even then the air is heated up only by a 3 - 7 degrees Celsius. Using extra heat should be kept at the minimum allowable level employing for this purpose the MCD. It is recommended that in the climate that is the mixture of maritime and continental climates the heater should provide the maximum power at the level of 0.42 kW/m^2 of the floor area (in the SI metric system of units 1 kilowatt = 1 kilojoule per second, 1 kW = 1 kJ/s). This value is the product of:

a) assumed air volume flow per 1 m^2 of floor area (0.07 m^3/s, suggested in Table 4.3),
b) the increase of the heat content (enthalpy) of air that must be heated to reduce its RH from 87 to 65% as shown in Figure 4.6 (e.g. 44.2 – 39.6 = 4.6 kJ/kg$_{dry\text{-}air}$); air parameters used for calculation, shown in Table 4.4, were determined using psychrometric relationships,
c) specific density of the heated air (e.g. 1.19 kg$_{dry\text{-}air}$/m^3 shown in Table 4.4),
d) the factor of the heat losses from a heater (e.g. typical value of 1.1).

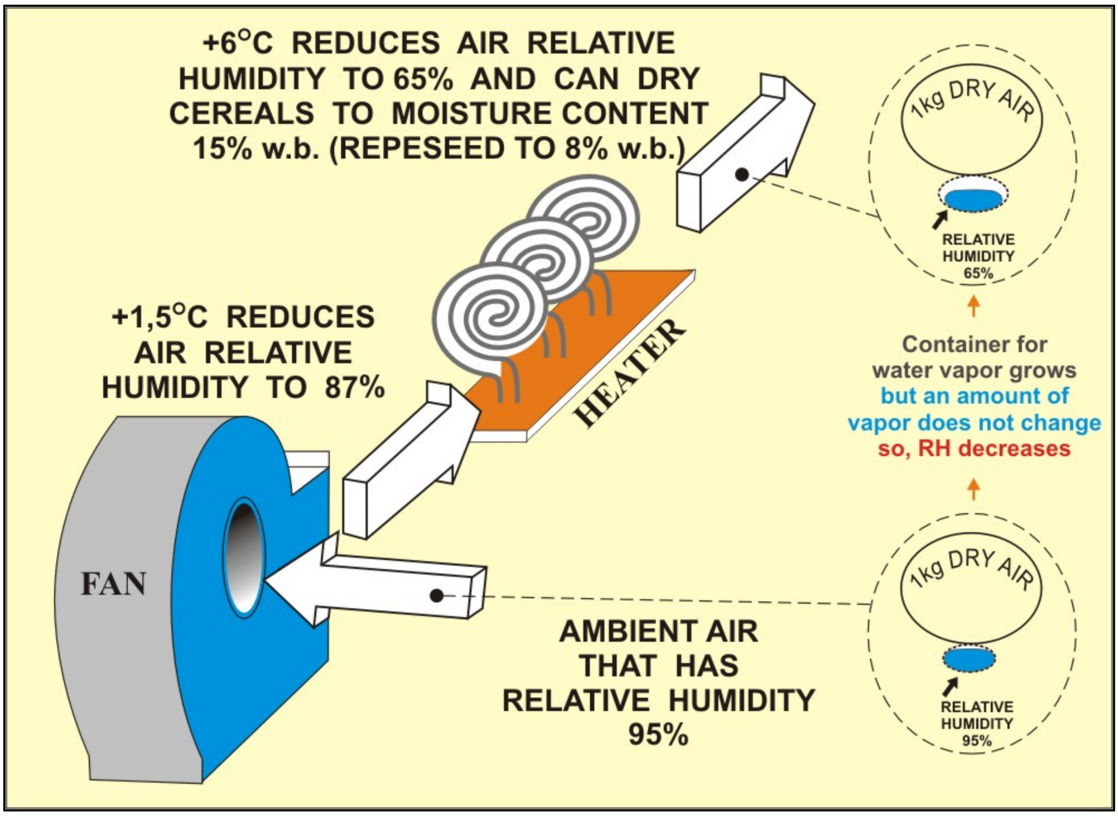

Figure 4.6. Heater and fan increase the air drying potential. The conceptual models of moist air (on the right hand side), explained in Figures 2.1 and 2.2 were used. (It was assumed that the MCD switch off the fan and heater when air RH is higher than 95%.)

Table 4.4. Changes of air parameters during the heating shown in Figure 4.6.

Air	RH	Temp.	Heat content (enthalpy)	Specific density
	%	°C	kJ/kg$_{dry\text{-}air}$	kg$_{dry\text{-}air}$/m^3
Ambient	95	14*	38.0	1.21
Compressed by a fan	87	15.5	39.6	1.20
Heated by a heater	65	20	44.2	1.19

* typical temperature for RH=95% in the climate that is the mixture of maritime and continental climates

MEASURING-CONTROL DEVICE (MCD)

Although this was mentioned in the previous Chapter, it will be explained in more detail in the Part 2 of the handbook.

<u>Question 4.4.</u> What technical clues can be useful in the situation when one would like to employ the near-ambient method for drying grain?

The remarks presented below were taken from handbooks for American and British farmers (Friesen and Huminicki 1987, McLean 1989, MWPS-13 1988). One of the important problems is: how the silo or on-floor storage is filled. In general, three ways of filling are employed (MWPS-13 1988):

1. rapid filling during one or two days depending on the quantity of grain delivered from the combine-harvester,
2. layer filling; depending on the initial grain moisture content, one fourth, one third or half of the drying chamber is filled every successive week,
3. controlled filling – similar to layer filling but in this method the amount of the grain added each time as well as the frequency of filling depend on the moisture content of the grain harvested by the combine harvester as well as on how well the grain in the chamber has already been dried.

The choice of the filling method depends on the specific situation on a given farm.

The most important problem in the near-ambient drying is to understand interrelationships between the air flow, temperature of air and grain, grain moisture content and the thickness of the grain bed. The best way to increase the drying rate is to increase the velocity of the air flow through the grain layer. The velocity of the air flow through grain can be increased for a given fan by decreasing the thickness of the grain bed.

Increasing the temperature of the ventilation air does not reduce the required quantity of air needed for safe drying of a fixed bed of grain, and can lead to the occurrence of two unfavorable phenomena, a) the excessive drying of the grain layers situated at the inlet of the drying air, and b) condensation of water vapor (section 2.1.) and acceleration of mould development in the wet layers of grain at the air outlet, i.e. increase in the risk of grain spoilage. The increase of the drying air temperature (within appropriate limits) as a method of accelerating the drying process is used in high temperature driers but in situations when ventilated thin layers of grain are being continuously moved. When we want to increase the quantities of air at the design stage, it is necessary to use a bigger fan which is connected with increased power of the motor and higher investment expenditures. However, a bigger fan guarantees a higher degree of safety of the near-ambient drying process. Problems of achieving the required airflow delivered by a fan through bed of grain will be explained in more detail in the Part 2 of the handbook.

Some silos and on-floor stores are equipped with special devices for grain stirring (Figure 4.7). These stirrers are used in order to: a) mix two or more batches of grain in one silo, b) improve the speed of near-ambient drying by reducing the resistance of the grain bed to the air flow (drying time can be cut up to 50%). Some of the disadvantages of such stirrers include: increased costs of investment and maintenance, and reduction of the space in the top part of the silo where the device is usually mounted. The process of grain mixing only slightly increases mechanical damage to kernels. Improperly mounted stirrers can cause small particles of impurities to move downwards and increase the resistance of the grain layer to the flowing air. That is why grain cleaning can be very useful. On the other hand, when the mixing of grain is carried out properly, it reduces the resistance of the grain layer to the passage of air and increases the air flow by up to 30% without changing the fan (MWPS-13 1988). The increasing use of stirrers in the USA and the European Community shows that there are more advantages than disadvantages for farmers in these countries.

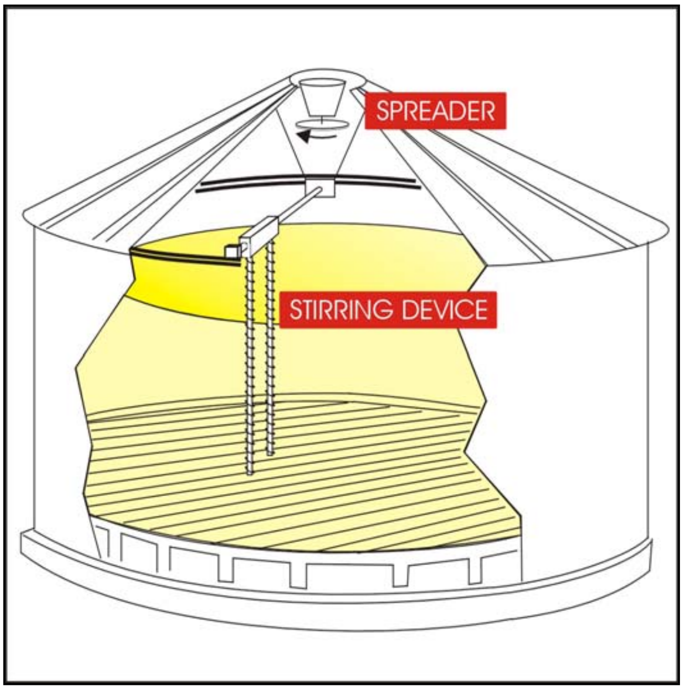

Figure 4.7. The grain stirring device and spreader.

4.4. SUMMARY FOR DRYING GRAIN IN BULK

1) Drying of grain in bulks, usually in the place where it will be stored, by ventilating using air at or near ambient temperatures has become more and more popular in many countries. The drying air temperature should be no higher than 5 – 8 °C above ambient – that is why the method is usually termed ”near-ambient drying”. Other popular terms used are: ”low-temperature drying”, “bulk

storage drying“ or “near-equilibrium drying”. Relative humidity of the drying air should be lower than the equilibrium value determined for the grain being dried. In European climatic conditions during most of the time of drying, atmospheric air with no additional heating can be used as the drying air – that is why this method of drying has very low specific energy consumption. The method can guarantee high quality of dried grain if drying is properly organized and controlled.

2) One can ask the question: how should I organize drying in bulk so that it is cheap and ensures high quality of dried grain? In the answer the key elements are:
   - a proper flow of air that should penetrate all spaces of the grain mass,
   - a correct relative humidity and temperature of the drying air,
   - a suitable control of the drying process.

   Drying air parameters should be controlled to ensure that wetting of the grain is eliminated and the drying of the wettest layers is finished before their quality could be reduced irrespective of the weather conditions. At the same time, over-drying of the driest layers should not occur at the end of the drying process.

3) What kind of equipment is essential to organize near-ambient drying? The most important are:
   silos or on-floor storage with perforated floors,
   fan and heater,
   monitoring and control unit, e.g. the “BIT-04” monitoring and control system (Figure 3.7).

   Air volume provided by the fan should be about 0.07 cubic meters per second for each square meter of area of the perforated floor (**0.07 $m^3/s{\cdot}m^2$ = 252 $m^3/h{\cdot}m^2$**). Grain depth should be chosen to ensure this airflow is achieved.

4) Maximum allowable grain depth depends on the initial grain moisture content at the beginning of drying:

Moisture content of cereal grain, [% w.b.]	Max allowable grain depth, [m]	Min airflow, [$m^3/h{\cdot}t$]]
17	6	55
20	3	111
22	1	332

5) The relative humidity of atmospheric air changes during drying and frequently is higher than the equilibrium relative humidity. It means that there is a **risk of wetting** of grain instead of drying it. That is why the relative humidity of air being blown into the mass of grain should be controlled and so, a Measuring-Control Device (MCD) should be applied, e.g. the “BIT-04” monitoring and control system capable of actuating a device reducing air relative humidity – typically a heater.

A control system should make sure that the relative humidity (RH) of the air ventilated into the mass of grain does not increase above the **set-point RH**. A suitable set-point RH is the equilibrium relative humidity reduced by an amount between 0 and about 10%, selectable by the user.

6) The simplest way of reducing relative humidity of air is heating it. Increasing air temperature by 1 °C results in decreasing air relative humidity about 5%. Heating should not be excessive - only the minimum necessary. The total heater power should be designed for the worst weather conditions in particular climatic conditions. In the climate of North and Central Europe the **total heater power** should be about **0.42 kW/m^2 of floor area**. It should be mentioned that wet grain just after harvest generates heat and additionally helps in reducing drying air relative humidity inside the ventilated mass of grain.

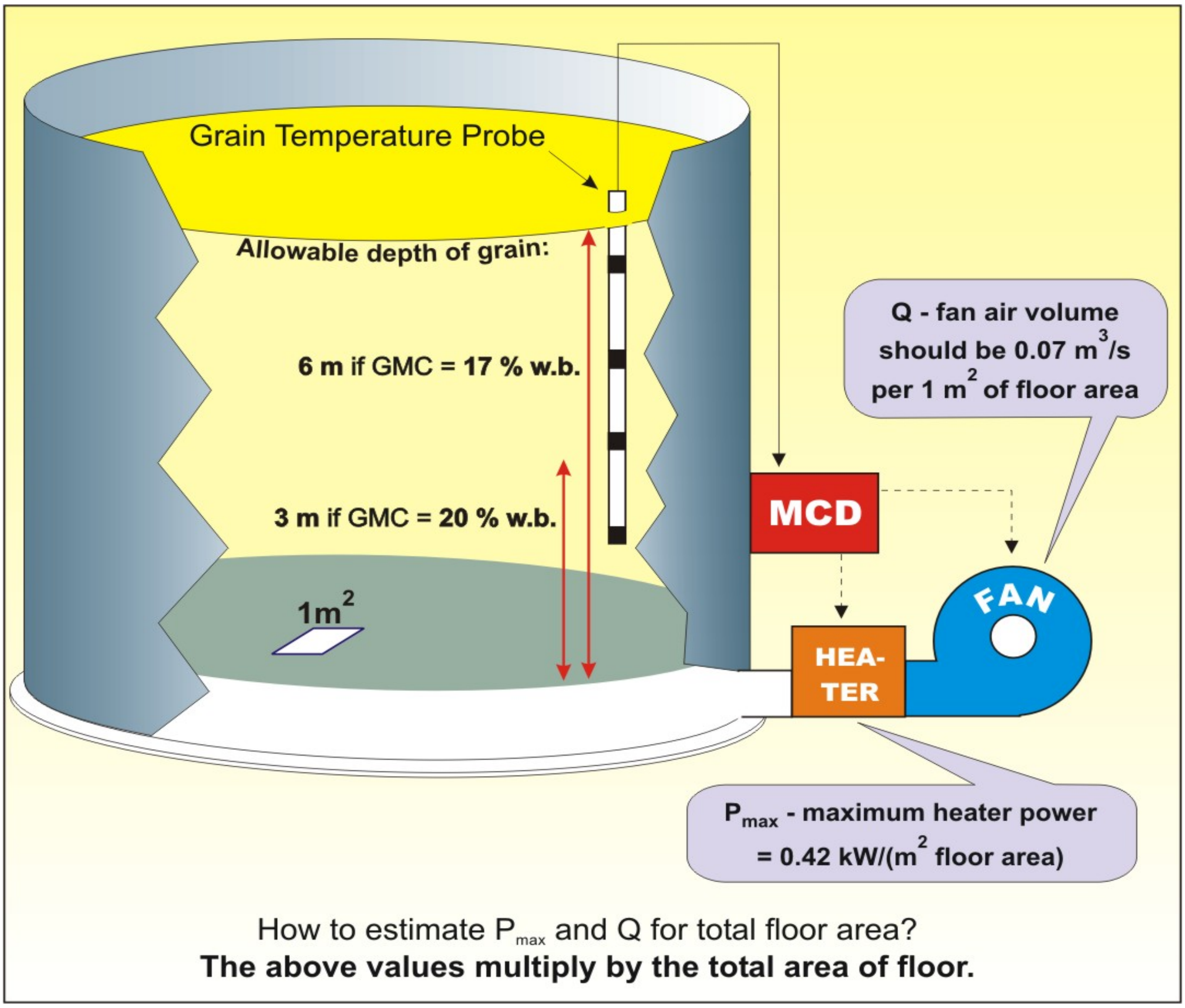

Figure 4.8. Drying of grain in bulk: basic information for the climate that is the mixture of maritime and continental climates (e.g. in Poland); MCD: Monitoring-Control Device; GMC: Grain Moisture Content.

7) **Attention!** Drying air **must not be heated too much** when it is used for ventilating into the deep bed of grain. Air heated too much takes too much water from the inlet layers of grain and when passing through deeper layers it is cooled down, resulting in the risk of condensation of water vapor in layers of grain near the outlet. Condensation of water vapor inside the mass of grain causes rewetting and this accelerates spoilage by mould growth.

When heating of air is under control on a minimum required level and only in the periods it is necessary, there is no risk of condensation of water in chilly layers, outlet for the drying air - usually top layers.

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