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Simultaneous Drying and Separation of Composite Agricultural Material for Hay Processing

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God for every thing

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1 PUBLICATIONS

Most of the chapters of this inform are articles published in international scientific journals as follows.

Lozano, O.F.; Hensel, O. Energy differences in a grass mixture drying. Agricultural Engineering International: CIGR Journal, 2013. 15(2) 284-292.

Lozano, O.F.; Hensel, O. Drying Homogeneity of Grass Mixture Components in a Rotary Movement. Drying Technology: An International Journal, 2012. 30 (16) 1931-1935. (doi:10.1080/07373937.2012.708889)

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Lozano, O.F.; Hensel, O. Hay Component Sieving by a Rotary Sieve with Lifting Flights. Drying Technology: An International Journal, 2014. 34 (13) 1560-1567. (doi:10.1080/07373937.2014.907303)

2 INTRODUCTION

In modern agricultural and agro-industrial activities, plenty of agricultural products composed by leaves and stems are present, [2.1] Among these; medicinal herbs tea, and specially grasses and forages require drying for their conditioning. A better understanding of the behavior of water remove in this kind of material is important in order to improve the process.

In general areas dedicated to the production of grass in Europe have decreased in recent years, because of the increase in maize silage and low prices of soy flour. In year 2007 grasslands occupied 39% of the agricultural area in EU, in this way permanent pastures covered 57 million ha and temporary grasslands, 10 million ha, [2.2].

While White Clover, despite of dominate in the pastures, is almost not used in silage production but for grazing; the Red Clover is most used for silage. Lucerne, by other hand, is used for silage, hay and dehydrated forage.

The grass- legume mixtures offer benefits like more production, increase of the forage intake, give the possibility of extend the harvest period, and mainly the providing of important amounts of Nitrogen to the plant-soil system, [2.3]. The use of grass mixtures promotes also effects like the increasing in the concentration of essential macro and micro-minerals in the herbage, [2.4]. Because of the Nitrogen fixation to soil, the clover is useful in mixtures regardless of the management, yield and location, [2.5].

In these grass mixtures, White Clover is the most important legume in temperate regions. Associated with grasses it gives high nutritional quality, and although it has decreased in the last decades, there is a new interest on it for environmental and economic reasons, [2.6].

On the other hand, Perennial Ryegrass is the more planted agricultural specie in Western Europe and more of the 98% of its production is ensiled, [2.7].

In accordance with [2.8]; in the European Union in year 2005, the market of animal feed was near 450 Mt of products with a price of 61 mill EUR, covering 47% of the livestock production. Foods sold (including dehydrated products) represented less than 10% of consumption of feed. Fodder (pasture, hay, dried fodder, etc.) represented about half of the feed by volume, nevertheless, as the intensification of the livestock increased, also raised the demand of food compounds in animal feed. (Between 30% and 35% in intensive farming).

In accordance to the figures of [2.2], for year 2007, European grass land was managed by 5.4 million holders, from which about 41 % were very small farmers with an Economic Size Unit less than one. Farms specialised in grazing livestock employed about 21% of total EU-27 agricultural labour force in 2007.

The dehydrated forages subject to benefit from EU community was 5 081 000 ton, or 96.7 % of the total assisted forage dried in 2004/2005.

In Europe, this agro industry occupied the order of 4500 industrial jobs in full time equivalents, including 3000 direct and 1500 induced. Direct permanent employment, across the 25 Counties in 2005 was about 2500 people. Temporary seasonal increased the workforce of approximately 650 full-time equivalents. Table 2.1 shows the kind of grass produced.

Table 2.1. Kind of grass production in Europe.
Source [2.8]

System	Under System	Localization
Field Crops	Alfalfa, No irrigated crop, in rotation with a dominant cereal	Spain, France, Italy, Romany, UK, East Germany, Denmark, Netherlands.
	Alfalfa irrigated	
Mixture	Grass	Spain
Milk systems	Alfalfa	France, South Germany,
	Prairies (grass)	South Germany, Netherlands, Denmark.

In general, there are two kinds of drying: Drying in the sun and Dehydration.

In dehydration, the grass is dried in rotary dryers at temperatures between 250 and 900°C, which makes a fast drying, keeping the qualities such as proteins, color and energy value.

Another way of dehydration is called “wet way” in which the grass is finely crushed and a separation between a protein-rich green juice and a torte rich in fiber is made, after the process the results are a torte, a protein paste and a green juice. In this system, as much as 40% of the fossil energy and 50 % of the greenhouse gasses emissions are saved.

In the dehydration process, the product abandons the dryer with moisture content below the 12 %, and enters with a moisture, which depends on the pretreatment after the harvest and on the region. It can be under 40 % if the forage remained few hours on the ground after the cut as in south Europe, or over 75 % without such pre-dying as in North Europe.

Due to the composition of this material, in general an uneven drying of the parts (leaves, stems), as described in the various chapters of this study, are presented. The biggest area and a more concentration of stomata in the leaves, makes that these dry faster than stems, even when they are attached together. This behavior makes that when the material is extracted from the dryer, its average has a desired moisture content but leaves are drier while the stems are wetter, this could lead to a fungi problem. Otherwise, if under this condition the material is even more dried until stems reach the desired moisture content, the leaves could be so dry that become crumble, in addition to the extra energy required.

The amount of energy consumed in the operation depends on this initial moisture content. And as the heat sources are mainly petrol derivate and carbon, this cost pushes the industry to seek technical solutions to reduce the energy consumption and recover the maximum heat in the process of dehydration in the dry way.

An estimate for energy consumption of the rotary dryer varies from 3 to 8 GJ/t depending upon the operating conditions and initial moisture content of the material, [1.9]. But there is a reduction in the energy consumption almost in Spain (which is the bigger producer of dried forages in Europe with 44%, after is Italy with 22 % and France with 21%) where 20% of the energy consume is provided by biomass, [2.10].

Depending of the initial moisture content of the product, the energy requirements could vary from 1.5 – 1.7 MJ-kg^{-1} dry product with an initial content of 35 g water-g^{-1} dry mass, and 10 MJ-kg^{-1} dry product if the initial moisture is near 65 g water-g^{-1} dry mass, and the average fuel consumption depends on the drying technology. [2.8].

In other hand the estimated cost of total digestible nutrients (TDN) is approximately 2.5 ¢ per pound for grazed forages compared to an estimated 7¢ per pound of TDN for hay or silage. The silage and haymaking are two to three times more expensive than grazing when compared on a per pound of TDN basis. In Europe the majority of forage is stored as silage while most forage in the United States is stored as hay. Also while hay usually represents the least expensive method of providing nutrients to cattle when grazing is not available, hay is relatively expensive and time-consuming to produce and feed, [2.11].

The objective of this research project was to determine the drying conditions which allow to reduce the differences in drying times of a mixture of grass, which is composed of leaves and stems of white clover and ryegrass, in such way that a separation of these components is made during the process, in order to get a more homogeneous dry product.

To achieve this objective, it was seek developing models that predict the behavior of several properties of the components of the mixture and allow to decide at which time the separation during drying should be made. It was also sought to explore a device to make the separation of the components using any of the properties of the material, whose value changes with the moisture content; as well as designing a prototype for the drying and separation.

The rotary dryers are fast drying means to pasture and forage, they are used in North America and Europe. For this reason, this type of dryers was chosen to investigate what conditions of design of a machine and it running may be appropriate to achieve a reduction in the difference in drying times and make a separation of materials once they have reached their final moisture content.

To meet these conditions, first a research on the differences in drying of the different components of the mixture and then the analysis of differences in drying time and energy required for each component was made.

Consequently, an analysis of the behavior of the various components of this mixture under the conditions of rotary drying was done, in order to find under which conditions of rotation, dryer geometry and air temperature a better uniformity of drying can be achieved.

The behaviour of the separation of the components at different moisture contents in a rotating sieve was studied, which is proposed as a mechanical means of separation of the material within the rotary drier.

Also a study of the aerodynamic characteristics of the components of the mixture with different moisture contents was developed, since air and the drum rotating motion move the material along the dryer.

Finally, with the studied parameters of drying and their relation with a rotary dryer, a prototype was proposed, which was optimized using Computational Fluid Dynamics CFD in order to find the position and size of the entry and exit of air with which the best air distribution and velocity is achieved.

The chapters of this document are papers that have been published along the research time in different scientific journals, which appear next to the title of each part.

A mixture of Ryegrass with clover, since this is a common mixture for animal feed, was chosen as a means of investigation of these differences, considering that in addition to the leaves and stems of a single plant, the material including several species.

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3 BASICS OF HAY LEAF AND STEM DRYING

In order to understand the differences in drying time of the mixture components of this study, an overview of the anatomy of the leaf and stems is made. Also a review of some research that have study the movement of the water from the tissues during the drying.

3.1 OVERVIEW OF THE ANATOMY OF LEAVES AND STEMS OF RYEGRASS AND WHITE CLOVER.

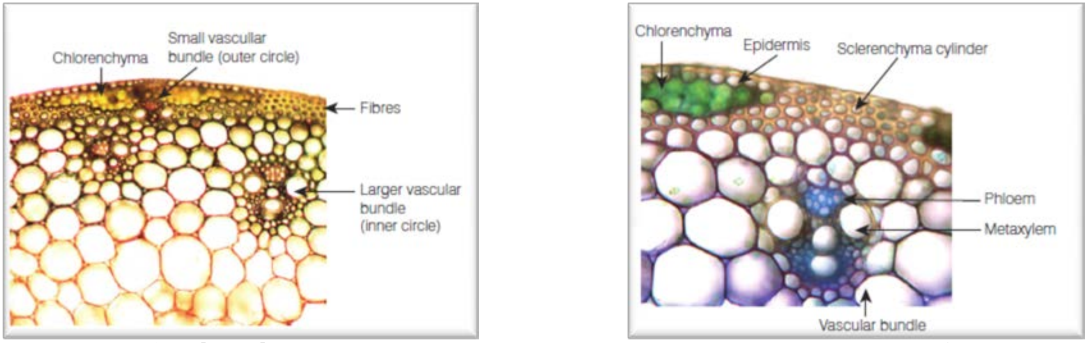
3.1.1 Ryegrass (*Lolium perenne*).

Source [3.1]

3.1.1.1 Stem structure

The stem of the *lolium Perenne* is hollow. (Figure 3.1 a). The peripheral tissues consist of sclerenchymatic elements for it stability. Chlorenchyma strands are embedded in the peripheral cylinder and bounded by the epidermis on the outer. There are at least two rings of vascular bundles within the upper third of a fully developed culm: a circle of very small vascular bundles embedded in the sclerenchyma cylinder (outer circle in Figure 3.1 c) and a circle of larger vascular bundles (inner circle in Figure 3.1 c).

a) Traverse section through a stem. **b)**. Enlarged view.



c) Enlarged view. **d)**. Enlarged view of *b*.

Figure 3.1 Traverse section through a *Lolium perenne* stem**.**

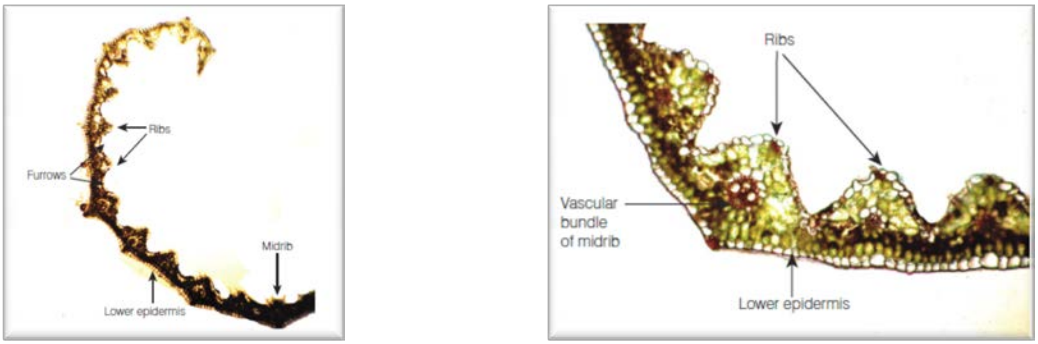
Source [3.1]

3.1.1.2 Leaf structure

A stem can have up to three adult leaves, one or two in growth and one or three in the process of senescence. In ryegrass, leaves are short-lived, then a fourth leaf emergence coincides with the dead of the first and each tiller maintains more or less three green leaves during its development.

Leaves blades have an almost flat surface on the lower or abaxial side. The upper or adaxial side is longitudinally ribbed, with ribs separated by furrows (Figure 3.2). The height of the ribs vary depending on the grow conditions.

Large vascular bundles are surrounded by a bundle sheath (or outer sheath) and by a mesotome sheath (or inner sheath).



a) Traverse section **b)** Vascular organization.

Figure 3.2. Traverse section of a leaf. *Lolium perenne*.
Source [3.1]

3.1.2 White Clover (*Trifolium rapens)*

3.1.2.1 Leaves

Leaflets have a dorsiventral structure (Fig. 3.3). Epidermis is one-layered while palisade tissue is composed of one to three layers of cylindrical cells. Spongy tissue has three to seven layers of cells, irregular in shape. In mesophyll, intercellular spaces of different size occur and extend to the abaxial epidermis. Mesophyll cells are densely arranged with small intercellular spaces. Collateral vascular bundles are arranged in a single row and surrounded by parenchymatous sheath cells. Larger vascular bundles have groups of sclerenchyma tissue on adaxial and abaxial sides. The main vein is more or less prominent abaxially and contains one large vascular bundle. Sclerenchyma tissue is better developed in the phloem part of the bundle. Between these two bundles sclerenchyma tissue is present. [3.2], [3.3].

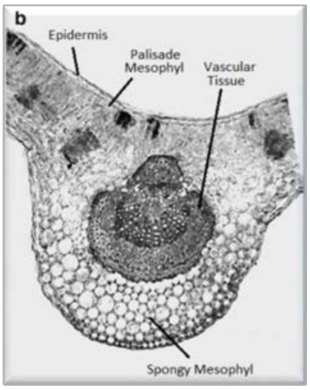


Figure 3.3. Clover Leaflet.
Adapted from [3.2]

3.1.2.2 Petioles, Stems.

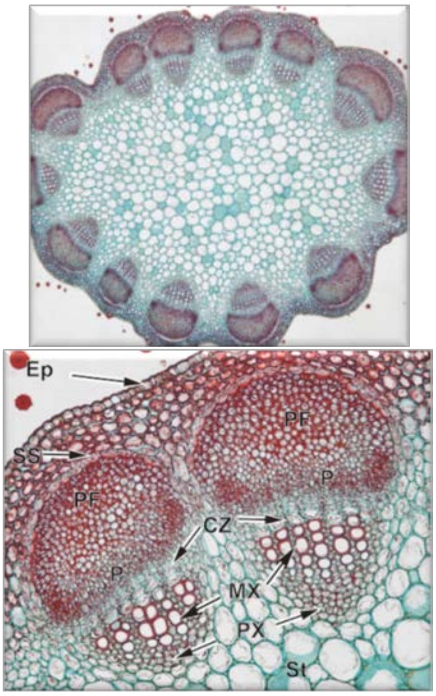
The leaf petioles are in average of 2 mm in diameter, pentagonal in section and hollow. Below the epidermis, there are five or six layers of rounded and green collenchymatous cells and below these, a similar thickness of larger rounded colourless pith cells, which extended to the hollow centre.

The thick stem (4-5 mm diameter) is approximately circular in section, but with the surface slightly raised above each of the normally fifteen stem bundles. Immediately below the epidermis, there is a layer of collenchyma of 7-8 cells thick. The remainder of the section, except that occupied by stem bundles, is filled with pith cells.

Petiole cross-section is pentagonal in section, with three prominent ribs: one central abaxial and two laterals adaxial. On the surface, there are one layer of small epidermal cells with thickened cell walls and glandular and non-glandular trichomes of the same type, as on the leaves. Subepidermally, one layer of five to six cells of collenchyma occurs. Cortex is composed of three to seven layers of rounded parenchyma cells containing chloroplasts. Figure 3.4.

Vascular bundles are arranged in a widely open arc. Usually, they are three large vascular bundles, one in each rib, and two or four small vascular bundles. Groups of sclerenchyma tissue are present in vascular bundles and are especially prominent in the phloem. Central part of petiole is composed of large parenchyma cells, which rarely, mostly in larger petioles, brake and form a cavity.

Stalk of Clover, *Trifolum Pratense*.
Source [3.15].



Epidermis (EP). Starch sheath (SS), phloem fibre caps (PF), primary phloem (P). Fascicular cambium zone (CZ) parenchymatous stele (St).
Source [3.16]

Figure 3.4. Clover Stem and petiole.

3.1.3 Tissues description

Source [2.4]

3.1.3.1 Vascular tissues

These tissues relate with conduction of food and water. They form a coherent system extending continuously through each organ and the entire plant. These tissues connect places of water intake and food synthesis with regions of growth, development and storage. The system contains two kinds of conducting tissues, the phloem (food conduction) and the xylem (water conduction).

The vascular system is embedded in the ground tissue, while the dermal tissue forms the outer covering. The principal differences in the structure of stem, leaf and root lie in the relative distribution of the vascular and ground tissues.

3.1.3.2 Epidermis

The epidermis has usually a thickness of one layer of cells. In some leaves the protodermal cells and their derivatives divide periclinally (parallel with the surface), resulting in a tissue consisting of several layers of ontogenetically related cells.

In leaves, the outermost layer of a multiple epidermis resembles an ordinary uniseriate epidermis in having a cuticle; the inner layers commonly contain few or no chloroplasts. One of the functions ascribed to the inner layers is the storage of water.

The common functions of the epidermis are reduction of water loss by transpiration, mechanical protection and gaseous exchange through stomata. Because of the compact arrangement of the cells and the presence of the relatively tough cuticle, the epidermis also offers mechanical support and adds stiffness to the stems.

The epidermis is a complex tissue composed of a wide variety of cell types, which reflect its multiplicity of functions. The groundmass of this tissue is composed by relatively unspecialized cells, the ordinary epidermal cells (also called ground cells, proper epidermal cells, unspecialized epidermal cells and pavement cells), and of more specialized cells dispersed throughout the mass. Among the more specialized cells are the guard cells of the stomata and a variety of appendages, the trichomes including the root hairs, which develop from epidermal cells of the roots.

3.1.3.3 Stomata

Stomata are openings in the epidermis, each bounded by two guard cells, which open and close a pore. The main role of stomata is regulating the exchange of water vapour and of CO2 between the plant and the atmosphere. Stomata occur on all aerial parts of the plant body and are most abundant on leaves.

There is a little or no gas exchange between the systems of intercellular spaces of the compartments in the leaves. The spatial distribution of the stomata and trichomes in the leaf epidermis is non-random and a minimum spacing exists between them.

Stomata in leaves of dicots, as T*rifolium*, are usually more numerous on the lower (abaxial) surface than on the upper (adaxial) one. Stomata may even be nearly absent from the upper epidermis. In many monocots, as *Lolium perenne*, and certain other plants, with vertically oriented leaves, they are approximately equal numbers of stomata per unit area on each side. A frequency of 50 to 300 stomata per mm^2 is representative for the lower surface of leaves of most mesophytes. The pores of the open stomata usually occupy 0.2 to 2% of the leaf surface area. Thus, the area for diffusion of gases through the stomata pores in the upper or the lower epidermis of a leaf is much less than the leaf surface area.

There are one report of stomata frequency on the upper surface of lucerne leaves between 211 and $700/mm^2$, and other of 169 mm^2 and 188 mm^2 for the upper and lower surfaces respectively. [3.14]

Stomata are also present on stems, but little quantitative evidence is available. When grass leaves are strongly ridged, all or most of the stomata may be on the upper (adaxial) surface as in *Festuca* or *Lolium* species, and they are situated on the lower slopes of the ridges.

For Italian ryegrass (*Lolium multiflor uni)* [3.14] mentions counts of 16 and 71 / mm^2 for the abaxial and adaxial sides respectively. For *Agrotis*, values varying between 72.9 and 121.4 / mm^2. In leaves of cocksfoot between 110 and 335 / mm^2. Despite the variation in stomata numbers, the ratio of pore area to leaf area remains remarkably constant. There is least frequent stomata on Red Clover stems and Italian Ryegrass pseudostems [3.5]. In Trifolium are reports of 221 and 118 stomas / cm^2 in the upper and lower part of the leaf respectively. [3.6]

3.2 DRYING DIFFERENCES BETWEEN PARTS OF A PLANT.

Several attempts have been made to explain the differences in drying behaviour between leaves and stems of different species, especially in grass and legumes.

In accordance with [3.6], the laminae dry faster than the petioles or stems and the drying is slower in the later stages. This conduces to a problem in these pastures for conservation as hay, since prolonged exposure increases the likelihood of spoilage.

In addition to the influence of the initial moisture content, [3.7] mention the importance of the ratio surface area to dry weight, in the sense that the species with a higher ratio, dries soon. The vegetative parts of Lolium, Festuca and Agrostis, Cynosurus and Anthoxanthum have a ratio in the order of 4 times greater than the reproductive parts (314:79). This relationship is fulfilled for these grasses except for Lolium.

Water is lost as vapour near to the plant surface. Drying curve reflects the resistance of water in the way to the evaporating site, plus the resistance to the diffusion of water vapour through the plant surface, [3.8]. The main barrier to water loss is the cuticle of leaves, because stomata close right after the cut. During the moisture content reduction, resistance to the loss of moisture is inverse to the weight of the free water present, [3.7]

For [3.7] this resistance to flow is composed by the cell resistance to the epidermis, the resistance of stomata resistance of boundary-layer, the cuticle resistance and the resistance diffuse within the mass of material; the two latter being the most important. The cuticle resistance might be independent of water content, but any resistance to moisture movement from individual cells to the skin would, presumably, vary with water content.

The resistance to the flow of steam in leaves of trifolium was measured to find the stomata, cuticle and external resistance in the path of the diffusion. 221 and 118 stomas / cm^2 in the upper and lower part of the leaf were found respectively. A cuticle well developed in the petioles but thin or absent in part of the leaves was found. These tissues are those that have a significant resistance to the passage of water vapour, [3.6]

Just after cutting, stomata resistances increase and cuticle transpiration becomes more important, in this way the variations of external resistance have little effect. In these early stages of drying, the moisture content and the resistance to moisture loss are lower in laminae than in petioles, and then the change from stomata to cuticle control of drying proceeds more rapidly in laminae.

As the drying proceeds, petiole and lamina resistance to movement of petiole liquid water to and through laminae increases, permitting laminae to dry to a moisture level at which they can no longer draw moisture from petioles even though some may still be slowly available. Thereafter, petiole moisture is lost only directly from petioles, probably by both stomata and cuticle transpiration for a time but later by cuticle transpiration alone.

However, the rapid and protracted drying rates presumably reflect, at least in part, the relative ease with which water can be removed from intercellular spaces and conducting vessels compared with its removal from cell sap and cytoplasm, [3.8].

The importance of the leaf in the extracting of water from the stem is remarked by [3.8]. The proportion of stem (including leaf sheath) ranges from 20% in vegetative tillers to 80% in reproductive tillers at anthesis. The structure and degree of exposure of stems also differs between growth stages. Differences in the drying characteristics of tillers at varying stages of development have been suggested. Plant structure therefore plays an important role in determining the rate of water loss, probably accounting for much of the differential drying of laminae and stems.

In general leaves dry faster than stems because the former have a larger surface area per unit of water contained than stems and the liquid water is closer to the surface in laminae. The surfaces of laminae also offer a lower diffusive resistance to water vapour, because of the numerous stomatal pores, [3.8]

In this way Stomata close soon after the beginning of drying; subsequently water vapour diffuses through the waxy cuticle over all uncut laminae and stem surfaces. If follows a continuing drying of laminae after stomata closure, which is faster compared with stems because a lower cuticle resistance for laminae. The resistance through cuticle is at least an order of magnitude greater than the stomata pathway, [3.3]. In other hand the variation in stem length would only have a small effect on water loss.

By a comparison between the drying of several grasses [3.9] found that, stomata close before a third of the water contained in the leaf has been lost, so that most of the water must pass through the cuticle, which covers all uncut leaf surfaces. Grass leaves aid the loss of water held in the associated stem or pseudostem, the process continues until the water concentration of the leaf has fallen to about 0.5 g/g dry mass. After leaf aid ceased, stem fraction continue, in some grasses due to the big proportion of pseudostems in the vegetative parts, which dry faster than the true stems of reproductive, in the later stages of drying.

For [3.6] 18.9 % of the petiole moisture was loss because of the leaf transpiration, and this reduction ceased when the lamina and petiole moisture content was approximately 2.0 and 4.0 g water/g dry mass, respectively. They concluded that some petiole moisture is lost via the laminae and this may result in more rapid overall drying than if petiole moisture were lost only directly from petiole surfaces, which also happen for soybean, sweet clover and lucerne. The variation of petiole moisture content at cessation of movement to the laminae indicated failure of laminae to transpire some petiole moisture, which might be considered to have still been readily available

The effect of the leaf aid, is broken when this and petiole are separated. In this case, moisture contents of attached petioles were lower than those of detached petioles and those of attached laminae were higher than those of detached laminae in tillers of White Clover. The effect of the separation is the reduction of the overall rate of mixture loss because the reduction of the loss of petiole moisture through the laminae, [3.6]

3.3 GRASS SPOILAGE

They are many reports on the apparition of mould and spoilage in hay as consequence of it moisture content.

Some studies has shown the moisture content limit for the hay in order to avoid the spoilage.

In accordance with [3.10] for perennial grasses, the mass fraction of water must be less than 20% to reduce the risk of detrimental biological activity in the stored bales, [3.11], as well as [3.12], for Alfalfa. [3.13] states the limit in the 15 %.

The presence of moulds in the hay reduces acceptability and feeding value. Feeding mouldy hay often results in lower dry matter intake, reduced weight gains or milk production, and poor efficiency compared with mold-free hay. [3.12].

For [3.13] is the water activity and not moisture content which influence the time required for the appearance of fungal fruiting bodies on both alfalfa stems and leaves. In this way, for alfalfa stems at 19.4% of moisture content, which corresponds to a water activity of 0.80, fruiting bodies appear after 22.5 days.

In this case, since leaves and stems have different composition and moisture content, then have different behaviour of spoilage. Stems have a greater spoilage potential than leaves, because these last have less water activity. In consequence, in the bale when the stems release moisture, increase the water activity of bale body and transfer to it factors that stimulate fungal development.

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4 ENERGY DIFFERENCES IN A GRASS MIXTURE DRYING

4.1 ABSTRACT

To understand the energy differences in the drying process of a mixture of grasses, in which the tissue dries at different rates, an analysis of the Isotherm Curves, Drying Curves, Vaporizing enthalpy and Latent Heat of Ryegrass and White Clover was made. Data of Equilibrium Moisture Content was obtained from literature and drying curves were developed in the drying lab. In general, White Clover Leaves dries first and the White Clover Stems slowest. The Isotherm Curves of the parts of the ryegrass was similar, but not the White Clover parts. Drying curves are different for every part in each temperature, but for all the plants and plant parts the drying is similar at 75 and 60°C. Vaporization Enthalpy is very similar for the two plants and plant parts, for almost all the Moisture Contents. The heat of vaporization during the drying was calculated; Ryegrass needs more heat for evaporating water than the White Clover parts.

Key words: Grass drying energy, isotherms, vapour enthalpy, grass mixture drying.

4.2 INTRODUCTION

Grazed mixed pastures are important for milk and meat production. In a prairie with grass and legumes the grass takes advantages of the Nitrogen fixed in the soil by the legumes. On the other hand, with several species a prairie is more persistence and has more productivity than with single species, also with the combination of plants of different life cycle it can hold dry or wet seasons, the production is longer and less seasonal. Species with several root depth take more advantage of the water resources.

Drying of a mixture of grass is an extended practice that subjects the species to the effect of hot air, which reduces the moisture content of each plant and of the plant parts to the desired final moisture in different time. Under the same condition of air, the time of drying of several species varies between each other according to the initial moisture content, plant morphology, the species and the age of the forage. Also many researchers have shown that leaves dry faster than stems in several plants and not only grass specie: in alfalfa [4.1], [4.2], [4.3]; in tall fescue and perennial ryegrass [4.4]; in White Clover [4.5]; in Jew’s mallow [4.6], spearmint and parsley herbs, in Coriander [4.7].

In many dryer plants in Europe and North America, direct contact type rotary drum dryers are often used for forages, which produce uniform product quality because of their long residence time and relative good mixing of the product. In these driers the energy consumption is between 3 and 8 MJ kg^{-1} dry product. If the dryer is badly designed or operated it could lead to failures in the quality and to more energy consumption [4.8].

Depending of the initial moisture content (χ_0) of the product the energy requirements could vary from 1.5 – 1.7 MJ kg^{-1} dry product, with an initial χ of 35 g water g^{-1} dry mass, and 10

MJ kg^{-1} dry product if the initial χ is near 65 g water g^{-1} dry mass, and the average fuel consumption depends on the drying technology. [4.9].

This way, when there are differences in the evaporation rate of the parts of the mixture, some energy could be saved if the already dried parts where pulled out of the dryer. On the other hand, with the over drying of one part there is a reduction in the quality of the final product, because the material can crumble during or after the process, which could lead to losses.

The objective of this research was making a comparison of the theoretical energy required to dry the parts of a mixture of grass composed by White Clover and Ryegrass. To do this, the analysis of the isotherms, drying curves and energy of drying of their stems, leaves and the complete plant were made. This way literature was employed while missing data were developed by own.

4.3 MATERIALS AND METHODS

In order to characterize and understand the differences of the drying behavior and heat energy required of one Ryegrass and White Clover mixture, some parameters of their performance were analyzed and compared between each other. In this way Isotherms, Drying Curves, Evaporation Enthalpy and Latent Heat were used for the comparison.

Isotherm and drying data was the base for all the comparisons, however, while the isotherm data were obtained from the literature, drying data where developed directly in the lab. With this data, Evaporation Enthalpy and Latent Heat during the drying were calculated and compared. Every of these parameters were obtained for the entire plant and the plant parts.

In [4.10] are reported data of Isotherms of White Clover Leaves and Stems, but not of the whole plant, then data of the whole plant Red Clover Extra Green and Brown were used from [11]. In the same way, Isotherm data of Leaves and Stems of Ryegrass are available in [4.10].

4.3.1 Isotherms

Normally Isotherms are expressed in the form of models; the most used are GAB, Henderson, Chung and Pfost, Halsey and Oswin. For this analysis, the Isotherm models reported by [4.11] and [4.10] were used to make the comparisons, taking in account to choose the reported model which has the minimum Standard Error.

The parameters of Isotherm Models of Ryegrass, the whole plant of Red Clover Green and Brown and the stems and leaves of White Clover are summarized in Table 4.1, which also includes the temperature at which the data were obtained, and the path i.e. if the isotherm corresponds to adsorption, desorption, or both.

In the report of [4.10], the isotherms of the material are shown as the curves, but there are not any models, then a regression was made and the parameters of the best one are shown in Table 4.1.

The Isotherms of the parts or of the plants were compared in the form of parallel lines, in which the slope is adjusted to be the same for all and the intercept of the line is allowed to vary. To do this, the data where transformed in order to fit the linear form of Oswin Modified and Halsey Modified as is shown in Equations 4.1 and 4.2.

Table 4.1. Parameters of the Isotherm models used.

Source	Tissue	Path	Isotherm Model	Constants			S.E.	T (°C)	Model in comparison
				a	b	c			
ASAE (2007)	Red Clover Extra Green	Mix	Halsey modified	3,8949	0,0200	2,0146	0,02	27	Halsey Modified
	Red Clover Brown	Mix	Halsey Modified	4,0939	0,0100	2,0029	0,03	29	
Shepherd (1956)	White Clover. Leaves.	Ads	Halsey Modified	3,867	-0,018	1,441	0,014	20	Oswin Modified
	White Clover Stems	Ads	Oswin Modified	18,637	-0,133	1,718	0,021		
	Ryegrass Leaves	Ads	Oswin Modified	16,4090	-0,2330	2,0490	0,002		
	Ryegrass Stems	Ads	Oswin Modified	17,0370	-0,2180	1,7680	0,005		
	Ryegrass Plant	Ads	Oswin Modified	16,2960	0,2240	1,7160	0,001	30	
	Ryegrass Plant	Des	Oswin Modified	18,6750	-0,2870	1,7310	0,026	30	

Linear Oswin Modified:

$$\ln\left(\chi_{eq}\right) = -\frac{1}{c}.\ln(a + b.T) - \frac{1}{c}.ln\left(\frac{1-U}{U}\right) \tag{4.1}$$

Linear Halsey Modified:

$$\ln\left(\chi_{eq}\right) = \frac{a + b.T}{c} - \frac{\ln\left(-\ln\left(U\right)\right)}{c} \tag{4.2}$$

4.3.2 Drying curves

The drying curves of each part or plant were developed in the lab in order to find one model of drying which allows making the comparison with the other parts or plants, and use the parameters of each model for the vaporization enthalpy analysis.

The samples were cut by hand from a field in Eichenberg- Hessen- Germany, with a mixture of Ryegrass and White Clover. In the lab the Ryegrass was separated from the White Clover; leaves and stems of the Clover were carefully detached. Three trays of each material were organized in a drier of axial flow, for every temperature of the air, after the determination of the initial Moisture Content of the samples.

The drying curves were obtained with air at 40, 60 and 75°C and 25 m min^{-1}, in the laboratory of drying of the Kassel University in Witzenhausen, in October of 2010.

The curves of MR – t, were adjusted to some of the models suggested by [4.12], shown in Table 4.2.

Table 4.2. Model Drying used.
Source [4.12]

Model Name	Expression
Lewis	MR = exp(-k.t)
Page	MR = $\exp(-k.t^n)$
Modified Page	MR = $\exp[(-k.t)^n]$
Henderson and Pabis	MR = a.exp(-k.t)
Yagcioglu et al or logarithmic	MR = a.exp(-k.t) + c

4.3.3 Evaporation enthalpy

The Evaporation Enthalpy h_v of each specie or tissue and the drying curves help to understand the differences in energy during the drying. To find the Evaporation Enthalpy the procedure of Othmer (1940) reported by [4.13] and the Equation 4.3, proposed by Clausius Clapeyron, were used.

$$\frac{dP_d}{d\theta} = \frac{h_v}{(V_v - V_1)}.T \tag{4.3}$$

Neglecting the value of V_1 in comparison with Vv, using the gas perfect relation for the water vapor and resolving the differential equation, the previous gives Equation 4.4:

$$lnP_v = \frac{h_v}{h_s}.lnP_s + f \tag{4.4}$$

This relation is a line in a log-log plane, with slope hv/hs.

The obtained results were fitted to the model suggested by Brooker (1984), [4.13] in Equation 4.5 and also to inverse, polynomial and quadratic models.

$$\frac{h_v}{h_s} - 1 = d.e^{-j \cdot \chi} \tag{4.5}$$

This way, with the value of the ratio h_v/h_s, it was possible to get the curves for h_v as function of χ.

Finally with both the curve of Vaporization Enthalpy in Equation 4.9 as function of the Moisture Content and the curve of Moisture Content as function of the time, for each part of the mixture, the amount of heat that it is required for the evaporation of free water in the tissues during the drying was calculated (Equations 4.6, 4.7 and 4.8).

For water: $L = m_w.h_v$ (4.6)

by definition: $m_w = \chi_{bd}*m_s$ (4.7)

χ varies with time in the drying process: $\chi_{db} = f(t)$ (4.8)

Vaporizing Enthalpy, for each tissue is: $h_v = h_{vs} *g(\chi)$, (Equation 5) (4.9)

Then q_{vap} will be calculated as Equation 4.10 using Equations 4.6, 4.7 and 4.8

$$L(t) = f(t)*g(f(t)).m_s.h_{vs} \tag{4.10}$$

The expresion for f(t) and g(χ) depends on each tissue and each specie. The vaporization heat can be calculated by unit of mass.

4.4 RESULTS AND DISCUSSION

4.4.1 Isotherms comparison

As the Figure 4.1 shows, the stems of ryegrass have the higher isotherms of the group, while the lowest correspond to the plants of the Red Clover Green and Brown, whose isotherm lines are almost the same. In the same way the leaves and the stems of the White Clover show similar isotherm lines in the scale of this figure and the same happens with the whole plant of Ryegrass in dessorption and sthe stems of Ryegrass in adsorption.

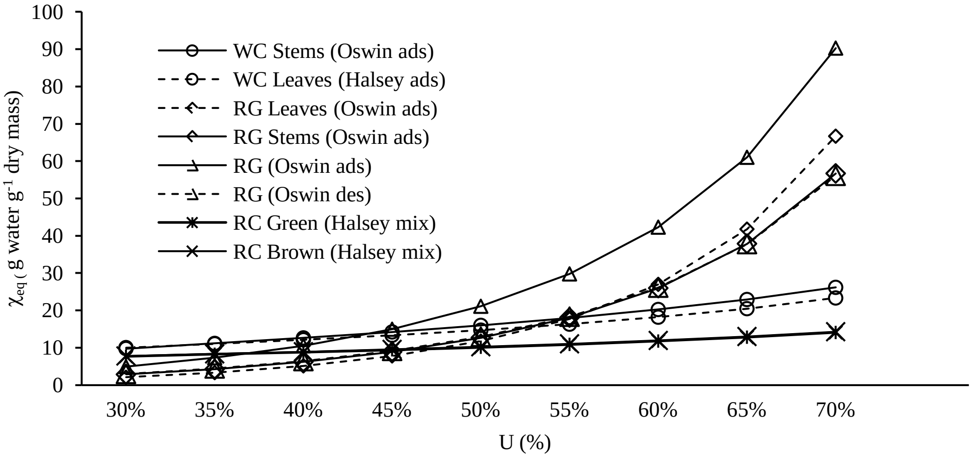

Figure 4.1. Isotherms of part and plant parts

The test with the isotherms transformed into straight lines shows how big this similiarityes are. Statistic F, with a certainty of 95.0% showed that in every case there was a good fitting between the lineal model and the data transformed into a linear form. Statistic T with a 97.5% certainty showed that the model parameters represent the data of the authors.

Figure 4.2a shows the lineal comparison of the isotherms for White Clover and Ryegrass with data of [4.10]. Figure 4.2b, corresponds to the comparison of the White Clover tissues and the whole plant in accordance with the data of [4.11]. In Figure 4.2c, there is the comparison of the isotherms for the tissues of the Ryegrass.

With the obtained result, in accordance with Figures 4.2a, 4.2b and 4.2c, a pair comparison with a 95.0% of confidence, between the most similar lines was made, as shown in the table 4.3

Table 4.3. Comparison of linearized isotherm data of several plants and tissues.

Tissue 1	Tissue 2	Coincidence
White Clover Stems	Red Clover Extra green (ASAE)	no
White Clover Stems	Red Clover Brown (ASAE)	no
Ryegrass Whole Plant Adsorption	Ryegrass Whole plant Desorption	Yes
Ryegrass Whole Plant Adsorption	Ryegrass Stems	Yes
Ryegrass Whole Plant Adsorption	Ryegrass Leaves	no
Ryegrass Whole plant Desorption	Ryegrass Stems	no
Ryegrass Whole Plant Desorption	Ryegrass Leaves	Yes

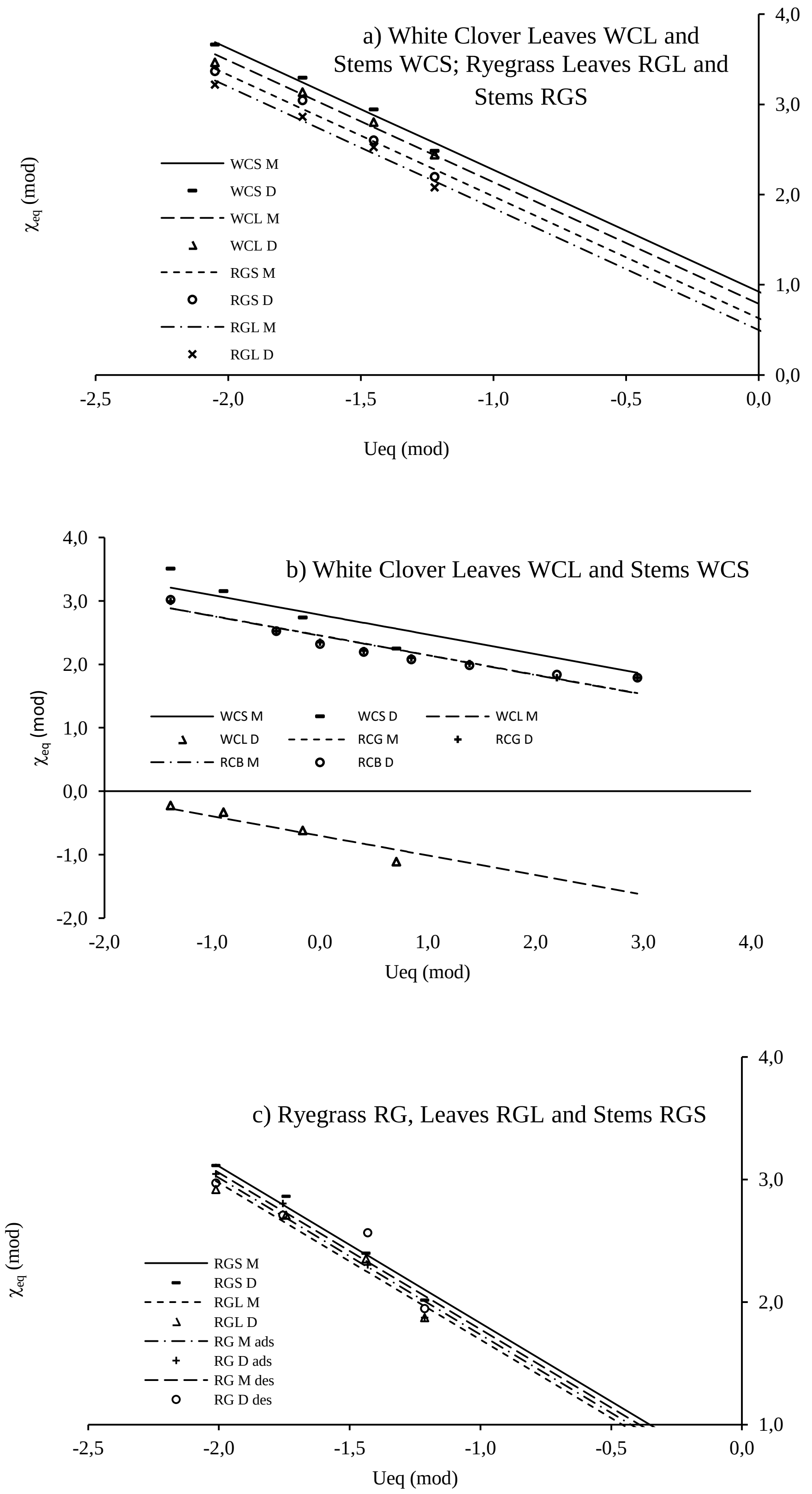

Figure 4.2. Transformed data and linear regression for Isotherms

a) White Clover and Ryegrass (T=22°C) Shepherd (1958). b) White Clover Leaves and Stems Shepherd (1958), and White Clover Green and Brown ASAE 2007. (T=30°C). c) Rye Grass Leaves and Stems and Ryegrass Whole plant. Shepherd (1964) (T=30°C). M: Model, D: Data

For this relation it could be concluded that there is almost complete similarity between all the tisues of the Ryegrass, but not between those of White Clover.This tendency is not an index of the performance of the drying curves, the vaporization entalpy or vaporization heat.

4.4.2 Drying curves

Figure 4.3 shows the drying curves of Ryegrass, White Clover, White Clover Leaves and White Clover Stemsat different temperatures. All the curves are in the form of MR-t.

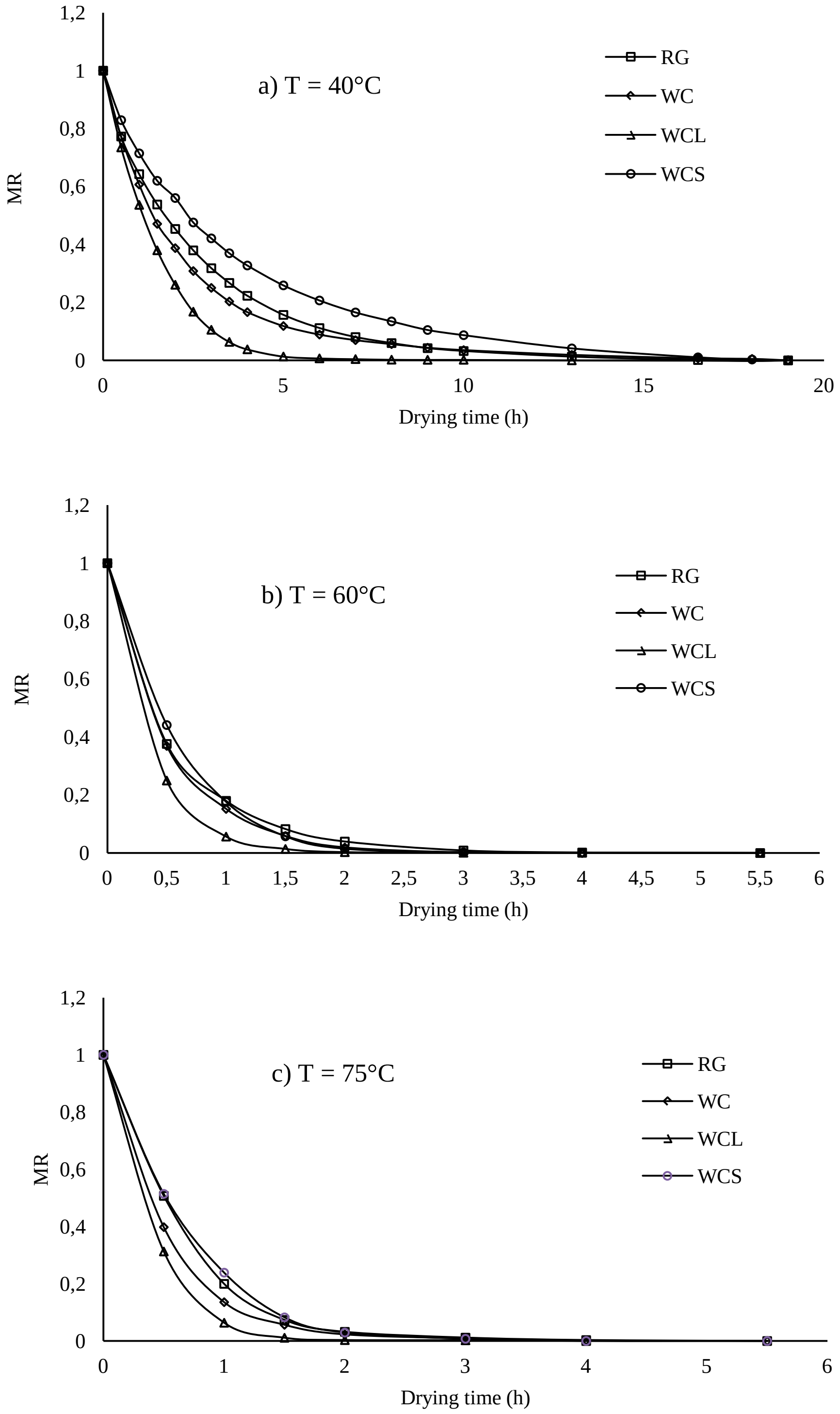

Figure 4.3. Drying Curves of Ryegrass, White Clover, Clover leaves and Clover stems.
a) at T=40°C, b) at T=60°C, c) at T=75°C

With air at 40°C, the Leaves of White Clover dryed faster, and the Stems of White Clover slower, the curve of the White Clover Plant is in the middle of its individual tissues and is similar to Ryegrass. This behavoir seems to be independent of the initial χ as showed in Table 4.4.

Table 4.4. χ_0 (g moisture g^{-1} dry mass)

T °C	Ryegrass	White Clover	White Clover Leaves	White Clover Stems
40	3,86	4,25	3,64	3,79
60	2,29	2,88	3,76	8,11
75	3,68	3,72	3,96	4,62

With air at 60 and 75°C, the drying curves were closer, althought the Leaves of the White Clover were always the first dryed.

From figure 4.3 it can be concluded that the behaviour of drying at 60 and 75°C is similar for these tissues.

Figure 4.4 is an example of the performance of the models for drying of Ryegrass at 40°C. This figure shows that Lewis model fit better than the others, although all were good predictor.

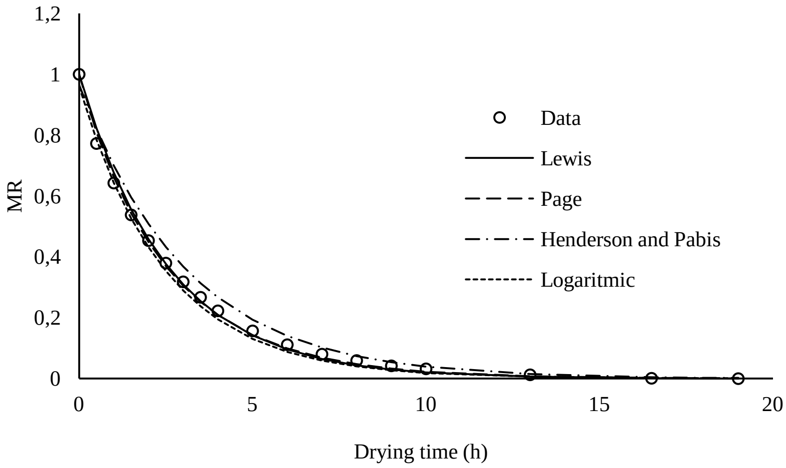

Figure 4.4. Fixing of models to drying of Ryegrass at 40°C

In order to find the k value, of the drying models, as function of T for every tissue, a nonlinear regession was made between the k costant obtained for every repetition and the temperature of the air; using SPSS 19.0.0.1 licenced to Kassel University. Table 4.5 summarizes the fitted models for the two plants and their tissues, and Tables 4.6 and 4.7 are the sumary of the fitting statistics for the Lewis moddel

Table 4.5. Constants for drying models.

Model		Ryegrass	White Clover	White Clover leaves	White Clover stems
Lewis	k	$-0.0005T^2+0.0901T - 2.4133$	$-0.022T^2+0.2952T - 7.806$	$-0.0037T^2+0.4742T - 12.389$	$-0.0021T^2 +0.2773T - 7.5253$
Page	k	$-0.0022T^2+0.2841T - 7.4313$	$-0.002T^2+0.2668T - 7.008$	$-0.0034T^2+0.4522T - 12.008$	$-0.0021T^2+0.2781T - 7.498$
	n	$0.0008T^2-0.0774T + 2.7774$	$0.0001T^2-0.0065T + 0.9746$	$0.0005T^2-0.0555T + 2.5443$	$-0.0004T^2 +0.048T - 0.4757$
Henderson and Pabis	a	$-1E-5T^2+0.002T+ 0.8724$	$-3E-5T^2+0.0039T + 0.862$	$4E-05T^2 -0.0048T + 1.1551$	$-7E-05T^2 +0.0093T + 0.6964$
	k	$-0.0026T^2+0.3286T - 8.6631$	$-0.024T^2+0.3153T - 8.3523$	$-0.0037T^2+0.4711T - 12.29$	$-0.0021T^2+0.2814T - 7.6543$
Logaritmic	a	$2E-05T^2 - 0.0005T + 0.9459$	$-4E-5T^2+0.0058T + 0.7949$	$5E-05T^2 -0.0067T + 1.2093$	$-9E-05T^2 +0.0123T + 0.6026$
	k	$-0.0028T^2 + 0.3552T - 9.3279$	$-0.022T^2+0.2926T - 7.7174$	$-0.0038T^2+0.4808T - 12.545$	$-0.002T^2+0.2704T - 7.3349$
	c	$-4E-05T^2 + 0.0036T - 0.0787$	$3E-05T^2-0.0039T + 0.1314$	$-2E-5T^2+0.0025T - 0.0734$	$3E-05T^2 -0.0044T + 0.1379$

Table 4.6. Fitting of the regressions for the Lewis model.

	75°C			60°C			40°C		
	Estimated k	S.E.	R^2	Estimated k	S.E.	R^2	Estimated k	S.E.	R^2
Ryegrass	1.526	0.062	0.987	1.189	0.081	0.986	0.389	0.013	0.961
Clover	1.8990	0.043	0.997	1.947	0.096	0.985	0.464	0.011	0.979
Clover Leaves	2.4420	0.115	0.99	2.793	0.069	0.998	0.681	0.011	0.993
Clover Stems	1.719	0.055	0.993	1.719	0.055	0.993	0.281	0.004	0.992

Table 4.7. Fitting of the k coefficient for the Lewis model.

	R^2	Std. Error of the Estimate	RSM	F	Sig.
Clover	0.843	0.375	2.255	16.065	0.004
Ryegrass	0.861	0.311	1.803	18.598	0.003
Clover Leaves	0.905	0.372	3.977	28.680	0.001
Clover Stems	0.963	0.151	17.789	78.429	0.000

4.4.3 Vaporization Entalpy, h

Table 4.8 summarizes the constants of the relation h/hs – MC of the Equation 4.5, although cuadratic and inverse models were tested, and in most of the cases these last showed better fitt, just for Red Clover Brown the expression 4.5, given by [4.16], and reported by several researchs is the best fitting. In order to maintain the standard for the hv/hvs relationship, the expressión 4.5 was used.

Table 4.8. Constans for the Equation 4.5.

Tissue	Isotherm Model	d	j	R^2
White Clover Leaves	Modified Halseydesorption	0.031	0.106	0.939
White Clover Stems	Modified Oswindesorption	0.011	0.052	0.993
Ryegrass Leaves	Modified Oswindesorption	0.036	0.102	0.981
Ryegrass Stems	Modified Oswindesorption	0.024	0.076	0.981
Ryegrass Whole plant	Modified Oswin Adsorption	0.024	0.078	0.977
Ryegrass Whole plant	Modified Oswindesorption	0.031	0.080	0.977
Red CloverBrown	Modified Halsey Mix	-0.051	0.238	0.989

Having in account that the enthalpy for saturated water vapor is given by Equation 4.11:

$$h_s = 3.11*10^6 – 2.38.10^3T \quad \text{(T in K)} \tag{4.11}$$

It is possible calculate the vaporizing enthalpy for each χ. Figure 4.5 shows the vaporizing enthalpy of leaves and stems of White Clover and of Ryegrass as function of χ (g water g^{-1} dry mass). The curves are drawn in the rank of χ reported by [4.11] and [4.10] and at 30°C of Temperature in desorption.

In accordance with Figure 4.5, it exists a very little differences between the Water Vaporization Enthalpy of all the plant and plant parts.

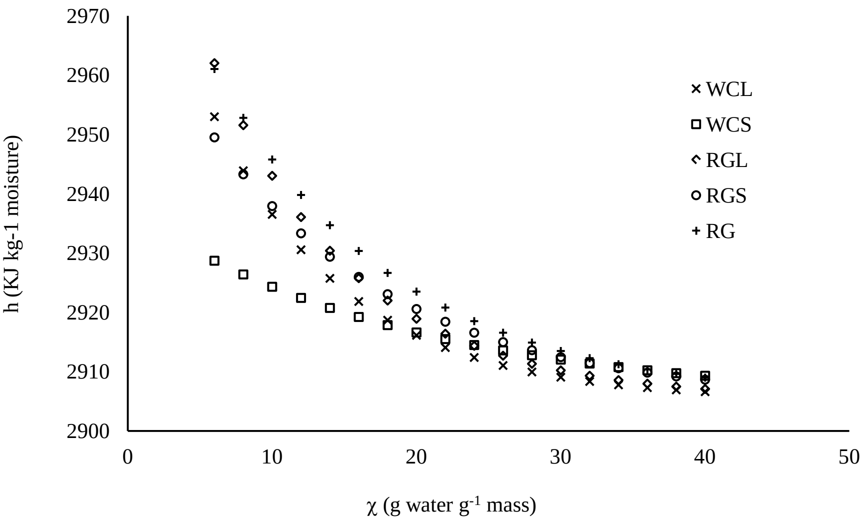

Figure 4.5. Vaporizing Enthalpy at 30°C for the grass species.

All the differences tend to zero at high Moisture Content, but they are higher for the lows. This behavoir could mean that, in the starting of the drying process, the energy required for vapouring the water of the different parts of a mixture of grass is very similar, but for the end of the process, after around χ of 18 g water g^{-1} dry mass, these differences grow a little.

The maximum differences are near 35 kJ kg^{-1} water, but if a ratio is made between the two tissues, the max difference is only close to the 1% of the maximum. This could mean that the differences in drying of each plant and parts, not depend on the enthalpy of the inside water, but on other factors.

4.4.4 Latent Heat for each specie and tissue

Latent heat (L) of Ryegrass and White Clover was calculated, using the Lewis model, whose constant χ_0 is explained in Table 4.4, the expresion for entalpy of Equation4.5, and the constants of Table 4.5. Then, the general expressions is Equation 4.12:

$$L = \left[e^{-k.t}.\left(\chi - \chi_{eq}\right) + \chi_{eq}\right]\left[d.e^{-j.\left[e^{-k.t}.\left(\chi_0 - \chi_{eq}\right) + \chi_{eq}\right]} + 1\right].h_{vs}.m_s \qquad (4.12)$$

In general in Figure 4.6, appears that stems of White Clover need more heat than the leaves, the entire plant of the clover and the Ryegrass. It is also remarkable that the leaves of White Clover need very less heat than the rest of the parts.

At the begining of the drying, the Red Clover Brown, had the higher L, but it decreased quickly and after 2 and 4 h had the same L as the Ryegrass.

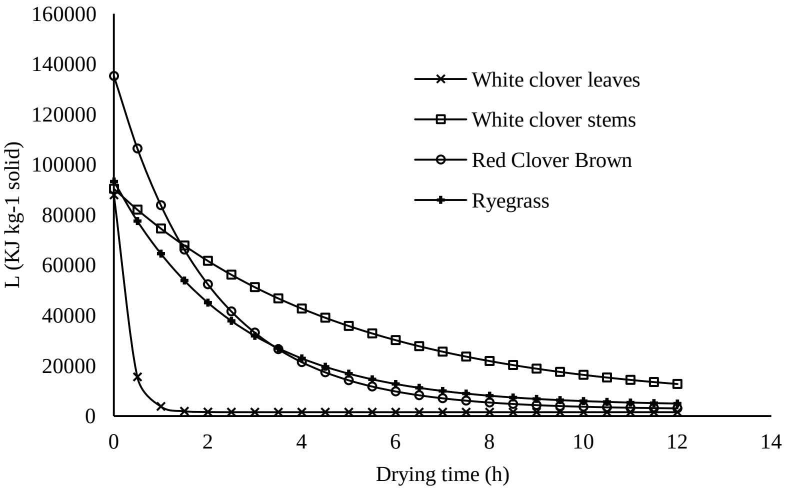

Figure 4.6. Evolution of Latent Heat in the drying process for each plant.

In order to calculate the total heat of the drying process, the next differencial equation must be writen Equation 4.13:

$$dh/d\chi = f'(\chi), \qquad d\chi/dt = g'(t)$$

Then

$$dhv = f'(\chi)*g'(t)*dt \tag{4.13}$$

Integration of Equation 4.13 along the time invested to reach the desired χ, should give the teorethical heat required to evaporate the free water present in the tissues (Equation 4.14).

$$\frac{dh}{d\chi} = -h_{vs}. d. j. e^{-j.\chi}$$

$$\frac{d\chi}{dt} = -k. X_{eq}. (\chi_0 - \chi_{eq})e^{-k.t}$$

$$dh = \left[-j. d. h_s. e^{-j.[(\chi_0-\chi_{eq}).e^{-k.t}+\chi_{eq}]}\right]. \left[-k. \chi_{eq}. (\chi_0 - \chi_{eq}). e^{-k.t}\right]. dt \tag{4.14}$$

Integration of Equation 4.14, between t_0 and t_1, gives the heat required to evaporate the free water in the drying process. The solution of 4.14 is Equation 4.15:

$$h = d. h_s. e^{-j.(\chi_{eq}+(\chi_0-\chi_{eq})e^{-k.t})}\Big|_{t_1}^{t_2} \tag{4.15}$$

Then, the Table 4.9 shows the time and the heat required to reach a χ of 0.2 and 0.1 g water g^{-1} dry mass.

Table 4.9. Heat required to reach χ = 0.20 and 0.10 g moisture g^{-1} dry mass.

Plant	Time (h) to χ=0.20	h_{vap} (kJ kg^{-1}dry mass)	Time (h) to χ=0.10	h_{vap} (kJ kg^{-1}dry mass)
Red Clover Brown	3.34	591	4.78	720
White Clover Leaves	2.44	177	3.49	203
Ryegrass	4.12	143	5.89	164
White Clover Stems	7.79	34	11.14	39

With the data and parameters for this model, in this case, the energy required for evaporate the water and reach a χ = 0.20 was 591 kJ kg^{-1} moisture for the whole plant of Red Clover. It was less than a half for its leaves and for the Ryegrass plant. The stems of White Clover require very less heat than for the other plants or tissues.

It is remarkable that the heat required for the leaves of the White Clover and for the plant of ryegrass is almost the same for all the process, and that is required much more for the Whole plant of Clover, and less for the stems of the White Clover.

Although this is a theoretical amount of heat required to evaporate the free water in the plants, it could serve as a guide to design dryers for a mix of material.

4.5 CONCLUSIONS

A general characterization of the main parameters of the drying of a grass mixture has been made. Intent of comparison between these parameters for every tissue and plant in the mixture was made in order to understand how homogenous the performance during the drying is.

Isotherm curves seem to be similar for the tissues of Ryegrass, but not for those of White Clover, and it was found no similarities between Ryegrass and White Clover. This could predict a different performance and energy requirements in the drying.

The time to dry these plants and tissues is almost the same for temperatures between 60 and 75°C, but there were differences for 40°C, which influence the energy requirements for the water evaporation.

The tissues or plants in the mix have few differences between their Vaporization Enthalpy as function of Moisture Content. This can be interpreted to be that the energy required to remove water of this tissues is almost the same for each moisture content during the drying process.

When the latent heat is calculated as function of time in the drying process, using the drying curves, it was found that the entire plant of White Clover requires more heat than the Ryegrass.

The white clover leaves, having the lowest values of Isotherms, are faster in drying; nevertheless, the L required to evaporate the water during the drying process is higher than other parts of the mixture.

On the other hand, the stems of White Clover, having the highest values of Isotherms, are the slowest in drying, and have the lowest vaporization enthalpy, then requires the lowest vaporization heat of the materials in the mixture.

The whole plants of Clover and the Ryegrass have a middle position in the mixture, related to isotherms, time in drying, and vaporization enthalpy. However, related to the vaporization heat the White clover requires the maximum heat and the ryegrass is in the middle of the mixture.

It can be conclude that among a mixture of species, the performance of every single part or plant is different, and the global overview of the Moisture Content or the Energy required for the drying masks the individual behaviour, which not only attempts against the quality of the dried product, but also the time and costs of the drying.

This way it is a desirable mechanism to handle the drying of each part, and to separate during the process the parts that have already reach the desired moisture content.

4.6 SYMBOL LIST

a, b, c:	Constants in the Isotherm Models.
k:	Constant in the Drying Models
d, j:	Constants in the Water Vapor Enthalpy – Moisture Content model
h:	Water Vapor Enthalpy
h_s:	Saturated Water Vapor Enthalpy
t:	Time
v_1:	Water liquid face volume
v_v:	Water vapor face volume
D:	Data
M:	Model
WC:	White Clover
RG:	Ryegrass
WCL:	White Clover Leaves
WCS:	White Clover Stems
RGL:	Ryegrass Leaves
RGS:	Ryegrass Stems
RCL:	Red Clover Leaves
RCS:	Red Clover Stems
MR:	Moisture Ratio
χ:	Moisture Content
χ_{db}:	Moisture Content in dry basis
χ_{eq}:	Equilibrium Moisture Content
χ_0:	Initial Moisture Content
m_w:	Mass of water
m_s:	Mass of solids
Ads:	Adsorption path in the isotherms determination.
Des:	Desorption path in the isotherms determination.
Mix:	Adsorption or Desorption path in the isotherms determination.
U:	Relative Moisture (dec.)
p_d:	Water Vapor Pressure
P_s:	Saturated Water Vapor Pressure.
S.E.:	Standard Error.
T:	Temperature
L:	Latent Heat of Vaporization
Δhv:	Difference in entalpy

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5 DRYING HOMOGENEITY OF A GRASS MIXTURE COMPONENTS IN A ROTARY MOVEMENT

5.1 ABSTRACT

A test of drying homogeneity of a mixture of white clover and ryegrass, in a rotary drum was performed. The tests were made at 40, 60 and 80°C, with drum speeds of 15, 20 and 30 rpm; flat and square flights were used, and the amount of the material was the 10% of the drum volume. The size of the flights was used to handle this volume of dry material. It was found that all the drying curves were fit to a single exponential model, and some regression was obtained to predict the moisture content of every part, changing the temperature and the drum speed. The results showed that the geometry of the flights has no effect on the homogeneity of the final moisture content. The best results were reached at 80 °C and 30 rpm, when the differences in time to reach 0.1 g water g^{-1} dry mass were less than 1 hour.

Keywords: Drying homogeneity; Grass drying; Leaves and Stems drying; rotary drum dryer.

5.2 INTRODUCTION

According to [5.1] in the Europe Union forage and grass cover most of the agricultural land area. In a prairie with grass and legumes this takes advantages of the Nitrogen fixed in the soil by the legumes. On other hand, a prairie is more persistent with several species and is more productivity than with only a single species, in addition, with a combination of plants of different life cycle, the prairie can hold dry or wet seasons and the production is longer and less seasonal. Species with several root depth take greater advantage of the water resources.

Make hay using hot air is an extended practice to dehydrate the species, which involves reducing the moisture content of each plant and of the plant's parts to the desired final moisture in different time periods.

In many plants drying operations in Europe and North America, direct contact-type rotary drum dryers, which produce uniform product quality due of the long residence time and relative good mixing of the product, are often used for forages. In these dryers the energy consumption is between 3 and 8 MJ kg^{-1} dry product. A poorly designed or operated dryer could lead to under- or over- drying of the material and greater energy consumption. [5.2]

Different flight geometries are used in the rotary dryers, which ensures the cascading of the material for contact with the drying air. According to [5.3], there are many designs of lifting flights, and it is important to select the correct size and shape to ensure the correct handling of the dry material. Among the varieties of flights are straight, 120° angled, right angled, extended circular and others.

The dryer design must consider that the volume occupied by the load of solids in the rotary dryer should be between 10 and 15% of the total dryer volume, and the volume of material transported by the flights is between 10 and 15% of the total material volume inside the dryer [5.4].

Under the same condition of air, the drying time for different species varies other according to their initial moisture content, plant morphology, species and the age of the forage. Many researchers have shown that leaves dry faster than stems in several plants, not just grass species including: Alfalfa [5.5], [5.6], and [5.7]; Tall fescue and perennial ryegrass, [5.8]; White Clover, [5.9]; Jew's mallow, spearmint and parsley herbs, [5.10] and Coriander, [5.11]. Nevertheless, it is still unknown under which drying conditions in rotary drying this differences in drying time can be avoided or reduced, keeping in mind that drying of hay is influenced by the internal water movement in the plant and factors external to the material, [5.5], which can accelerate or slow the drying.

The differences in drying time are important because of the use of energy. Depending on the initial moisture content of the material the energy requirements can vary from 1.5 – 1.7 MJ kg^{-1} dry product with an initial χ_0 of 35 g water g^{-1} dry mass, and 10 MJ kg^{-1} dry product if the initial χ_0 is close to 65 g water g^{-1} dry mass, and the average fuel consumption depends on the drying technology. [5.1].

When there are differences in the evaporation rate of the parts of the mixture, some energy could be saved if the parts that are already dried are pulled out of the dryer. In addition, when one part there is over dried, there is a reduction in the quality of the final product, because the material can crumble during or after the process, which can lead to losses. Therefore, it is necessary to find any condition with which a more uniform moisture condition of the parts is reached.

The objective of this research was establish which conditions of air temperature, rotary velocity and type of flight provides the best homogeneity in the final moisture content of the components of a mixture including the leaves and the stems of the white clover.

5.3 METHODOLOGY

A mixture of white clover (*Trifolium repens*) and ryegrass (*Lolium perenne*) in a proportion of 1:1 by weight, as it came from the field, was dried in a small rotary drum, in which the rotary speed, air temperature and the type of flight were interchanged. The material was collected from a field at the research station of Eichenberg–Hessen of the Kassel University during the first cut in June 2011.

The drum was a stainless steel cylinder of 480 mm in diameter and 315 mm in width and fine perforated wall to allow air circulation but avoid the material drip. Three flights were installed inside the cylinder, which were calculated to handle 10% of the volume of the material dried in the drum, and the volume of the material inside the drum was 10% of the volume of the device in order to avoid the kiln effect or overload of the device. The profile of the flights used was flat and square. In this case three flights, one each 120°, were used. A Plexiglas cover was provided in front of the device in order to be able to view the behavior of the material under the test, as shown in figure 5.1.

The rotary drum was located inside an oven with forced air circulation and temperature control, which provides air temperatures of 40, 60, and 80°C and ambient relative humidity of 70%. The rotary speed of the drum was controlled by an electrical controller at 15, 20 and 30 rpm. Two hundred fifty grams of material was used in each test.

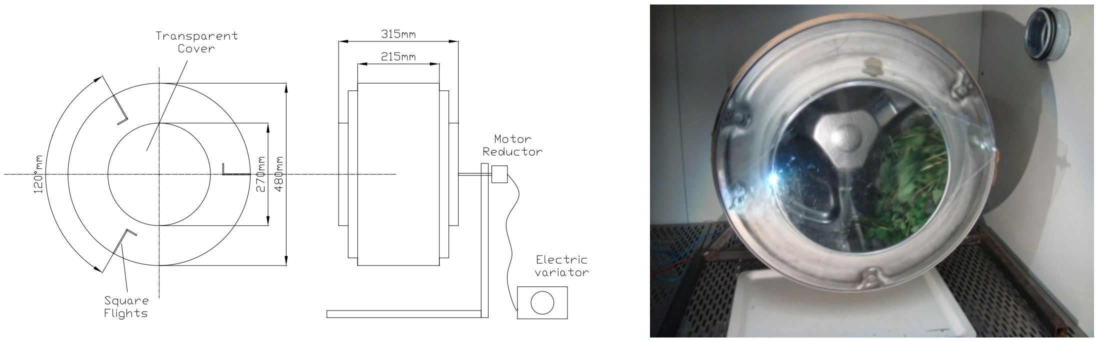

Figure 5.1. Drum Dryer used.

During drying, small samples of the material were extracted periodically (every 15 min during the first 60 min of drying, then every 30 min until 150 min of drying and then every 60 min until complete 300 min of drying at 60 and 80°C and until 540 min when drying at 40°C), separated into its components (ryegrass, clover, clover leaves and clover stems), weighed, and their moisture content was determined with the oven method, in order to determine the Moisture Content curve. The leaves and the stems of the clover were separated once the material was extracted. The drying curves were also compared with those obtained by thin layer drying using the same method of samples extraction and separation.

For the entire test, the curves of Moisture Ratio (MR) were adjusted to several expressions as in table 5.1.

Table 5.1. Drying Model used.
Source [5.12]

Model Name	Expression
Lewis	$MR = \exp(-k.t)$
Page	$MR = \exp(-k.t^n)$
Modified Page	$MR = \exp[(-k.t)^n]$
Henderson and Pabis	$MR = a.\exp(-k.t)$
Akpinar et al. or logarithmic	$MR = a.\exp(-k.t) + c$

5.4 RESULTS AND DISCUSSION

The data were subjected to regression analysis in SPSS 19.0.0.1, and it was found that the best fit was obtained with the simplest models.

In each experiment, which is a combination of type of flights, drying temperature and rotation speed, the moisture ratio was calculated and the regression to the five models was tested. The best model in all the cases was Page, with regression coefficients between 0.894 and 0.999.

Nevertheless, when a multivariate regression was made, taking the drum speed and the air temperature as variables, the model could not predict the experimental data well. This way, the Lewis model was used, in which the correlation coefficient was not as good, and varied between 0.748 and 0.997. For this model, a lineal regression between the value of *k* and *n* for every single T was found, keeping the geometry of the flight fixed. Table 5.2 shows the coefficients of the equation5.1.

Table 5.2. k function of the drum speed**.**

Flight		Flat		Square			Flat		Square	
Tissue	T (°C)	m	b	m	b	Tissue	m	b	m	b
Clover	40	0.0074	0.2264	0.0034	0.2773	Mixture	0.0079	0.1341	-0.0043	0.5966
	60	0.0164	0.5717	0.0070	0.7936		0.0324	0.2305	0.0353	0.0981
	80	0.0148	1.2516	0.1001	-0.5809		0.0087	1.6848	0.0337	0.5985
Clover Leaves	40	0.0161	0.1502	0.0010	0.4326	Clover	0.0148	0.1197	0.0087	0.3381
	60	0.0328	0.5684	0.0334	0.5324		0.0173	0.6195	0.0456	-0.0889
	80	0.0068	1.7571	0.1137	-0.1516		0.0641	0.0525	0.0455	0.2523
Clover Stems	40	0.0043	0.2086	0.0020	0.2109	Grass	0.0075	0.0851	0.0366	-0.2025
	60	0.0086	0.4147	0.0113	0.4007		0.0060	0.8160	0.0210	0.2315
	80	0.0044	0.8670	0.0709	-0.3337		0.0113	1.6157	0.0168	1.0105

$$MR = e^{-k.t} \tag{5.1}$$

$$k = m.n + b$$

Where

$\mathrm{M}R = \frac{\chi_i}{\chi_0}$

χ_0 = Initial Moisture Content: g water/g dry mass

χ_i = Moisture Content in any drying time: g water/g dry mass

t = Drying time (h)

n = Drum speed (rev/min)

m, b = Constants

The model for thin-layer drying was the same as the Lewis model and the constant *k* had the following relation to temperature:

Ryegrass	$k = -0.0005.T^2 + 0.0901.T - 2.413$
Clover	$k = -0.0022.T^2 + 0.2952.T - 7.806$
Clover Leaves	$k = -0.0037.T^2 + 0.4742.T - 12.389$
Clover Stems	$k = -0.0021.T^2 + 0.2773.T - 7.525$

A chart comparing drying curves was plotted. Figure 5.2 shows one example of the behavior of the material with flat flights.

With low drying temperatures all the material follows a flat and smooth drying curve in the nonlinear phase, until after 10 h it approaches $\chi_{eq.}$ For higher temperatures, the falling period was linear, and this time decreased as the temperature increased, to 2.5 h for 60°C and 1.5 h for 80°C. At 40°C, in contrast with all the other treatments, ryegrass required the minimal drying time.

In general terms the geometry of the flights did not to influence the order of drying of the mixture components. For flat and square flights, the clover stems and the ryegrass keep the high χ while the clover leaves remains with the lowest χ along the drying process for all the temperatures and rotation speeds.

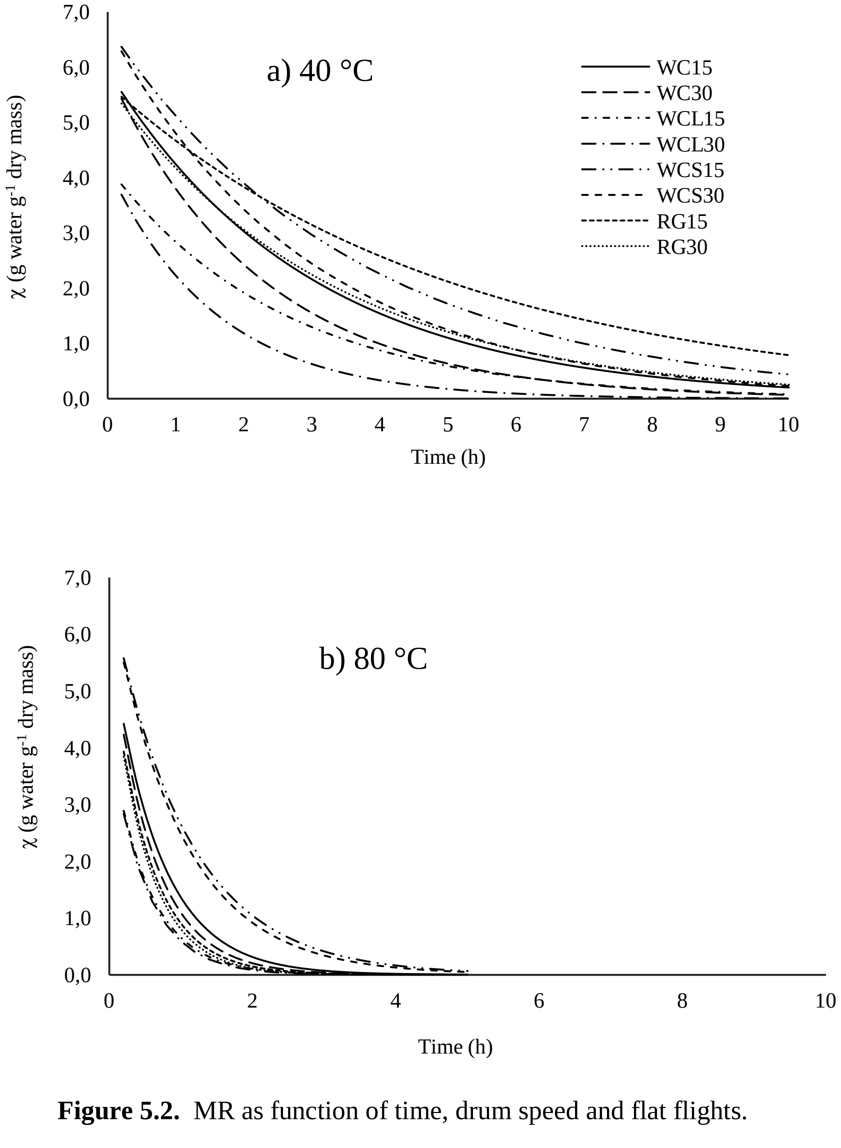

Figure 5.2. MR as function of time, drum speed and flat flights.

5.4.1 Moisture of the material at the end of the falling period

In order to compare the differences of the material after certain drying time, the time at which the curves begin to follow a flat path approaching the equilibrium moisture content, was selected. Figures 5.3 to 5.5.

As figure 5.3 shows, after 10 h at 40°C, the differences in the MR of the material were higher at low rotary speeds. With square flights the MR was lower than with flat flights at all the drum speed. This figure also shows that with rotation the final moisture content was lower than in the thin-layer drying. In all cases, the grass maintained a higher MR, even when it was lower for the other parts.

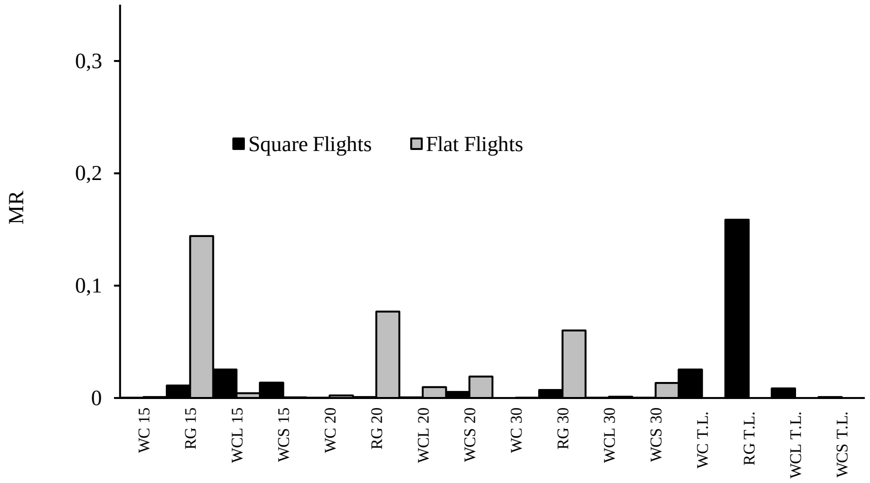

Figure 5.3. Moisture Ratio of the components at 10 hours of drying at 40°C.

After 2.5 h at 60°C, the drying curve at 15 rpm became flat and all the parts of the mixture had an MR less than 0.1, Figure 5.4. At this temperature, there are fewer differences in MR than at 40°C.

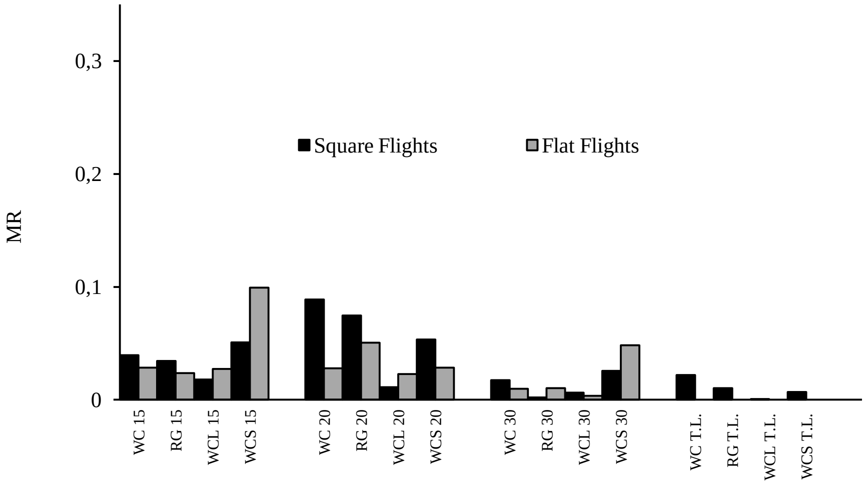

Figure 5.4. Moisture Ratio of the components at 2.5 hours of drying at 60 °C.

At 15 rpm with square flights all of the material reached a more or less uniform MR, whereas at 20 rpm the differences where greater. With flat flights at 15 and 20 rpm there were some differences, and the MR in general was lower than with the square geometry. At 30 rpm, for both flights, the differences were not important. In general, thin-layer drying had the best performance at 60°C.

After 1.5 h at 80°C, the drying curves stabilized and almost all the components had a MR less than 0.1. As figure 5.5 shows, with flat flights at all the drum speeds, the elements of the mixture did not have important differences. Nevertheless, with square flights, the moisture content of the ryegrass was still high even when the other material was almost completely dry. The rotation at all temperatures led to better results than in thin-layer drying.

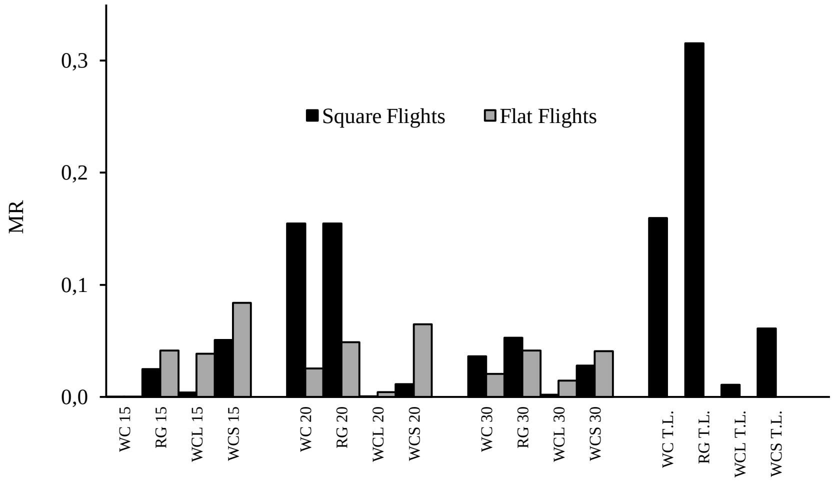

Figure 5.5. Moisture Ratio of the components at 1.5 hours of drying at 80°C.

5.4.2 Time to reach a desired MR

Figures 5.6 to 5.8 were produced to analyze the time required to achieve 0.1 g water g^{-1} dry mass, from initial χ_0 of 5.1 for grass, 5.4 for clover, 5.2 for a mixture, 4.1 for leaves and 6.7 for stems.

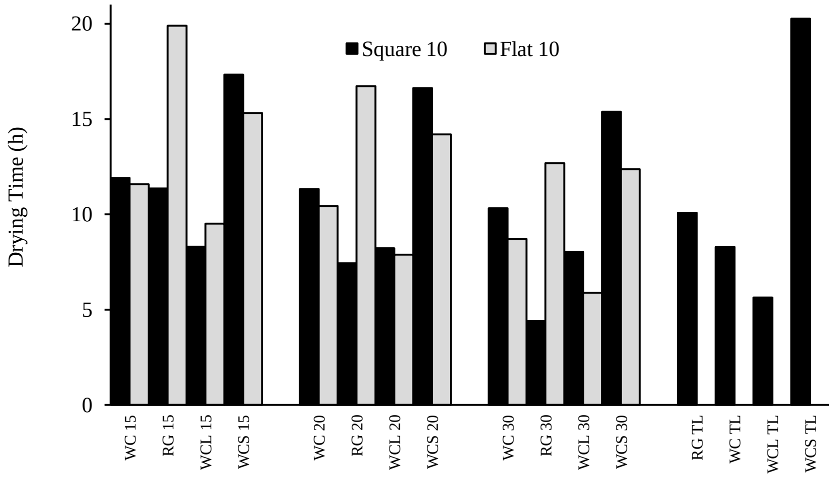

Figure 5.6. Time required reaching 0.1 g water g-1 dry mass at 40 °C.

When the drying temperature was 40°C, as figure 5.6 shows, the ryegrass took a longer time at 15 and 20 rpm to reach 0.1 g water g^{-1} dry mass with flat flights, followed by the clover stems. The maximum differences were 10.4 h at 15 rpm, 12.6 h at 20 rpm, and 8.3 h at 30 rpm. With square flights the times were shorter in general, but they were similar to those with flat flights; 10 h at 15 rpm, 9 h at 20 rpm and 11h at 30 rpm. Nevertheless, the differences were less than those required in thin-layer drying, when there was a difference of 14.6 h in drying time between the clover stems and the clover leaves.

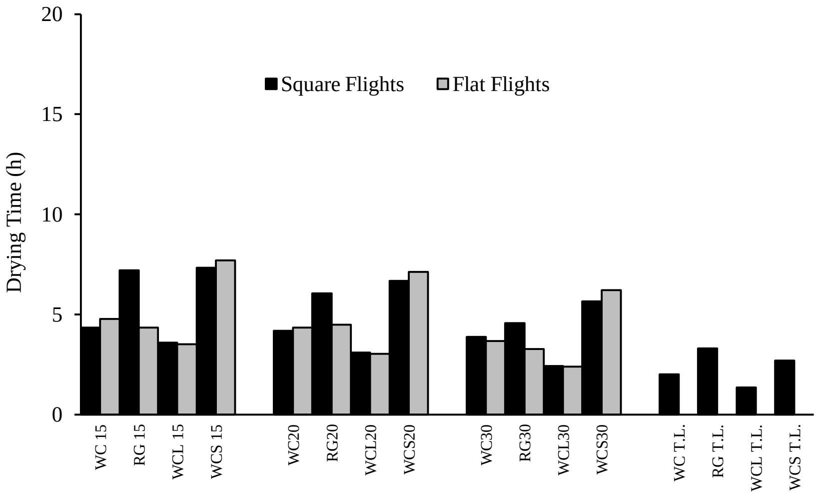

Figure 5.7. Time required reaching 0.1 g water g^{-1} dry mass at 60°C.

At 60°C, to achieve χ 0.1 g water g^{-1} dry mass, at all the drum speeds, the differences in time were similar, at 15 rpm the maximum difference in time were 3.7 h for square flights and 4.2 h for flat flights. At 20 rpm the differences was 3.6 h for square and 4.1 h for flat flights and at 30 rpm the difference was 3.2 h for square flights and 3.8 for flat flights. The smaller differences were for thin-layer drying, which was 2 h. Figure 5.7.

As figure 5.8 shows, at 80°C and 20 rpm, with flat and square flights, the differences in drying time were less than 2 h; at 30 rpm they were 1.45 h, and at 15 rpm the maximum difference was 3.3 h. The results were better at 30 rpm than in thin-layer drying.

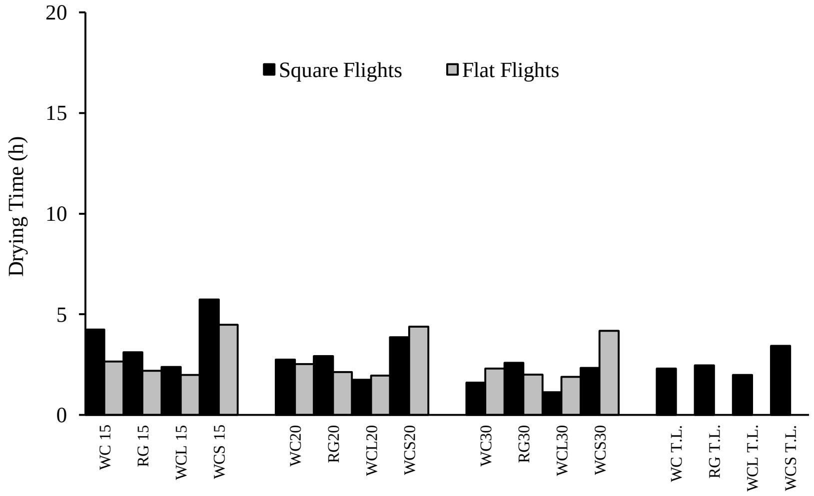

Figure 5.8. Time required reaching 0.1 g waterg-1 dry mass at 80°C.

5.5 CONCLUSIONS

The manipulation of variables such as drying air temperature, flights geometry and drum rotation speed was not the key to reaching a high homogenous moisture content of the parts of a mixture of grass. For all the conditions, the clover stems took the longest time to lose their moisture at all the temperatures, drum speeds and flight geometry, and the leaves reached their final moistures content sooner than the other parts of the mixture.

The flight geometry tested in this experiment did not show any observable effect on the reduction of the differences in drying. It was supposed that square flights, which allow better distribution of the particles along the upper part of the cylinder, and greater contact between the air and the material, could reduce the drying time of the ‘hard’ parts, but in this experiment, square flights did not have such effect.

The drum rotation speed had an effect on the reduction in the differences in drying time of the mixture components. Increasing in the drum speed reduced the time differences by 2 h at 40°C and 1 h at 80°C, when the drying times were shorter.

The greatest effect on the drying homogeneity was provided by the air temperature, because at higher temperatures the drying times were reduced and therefore the moisture content after the falling period was similar.

In general, 80°C and 30 rpm resulted in the best homogeneity in the moisture content and shortest time required to reach the final desired moisture content.

The behavior of this mixture is typical for medicinal and aromatic plants that require drying for their handling and preservation. It is recommended to develop a research like this for those plants, but also taking in account the variation in the chemical composition throughout the process.

The variation in process parameters led to a reduction in differences in the drying time but did not eliminate them. In future research it will be interesting to develop drying devices to make that segregate the parts as each part reaches the desired moisture content.

5.6 SYMBOL LIST

MR:	Moisture Ratio: χ_i/χ_0
χ_o:	Initial Moisture Content: g water g^{-1} dry mass.
χ_i:	Moisture Content in any drying time: g water g^{-1}dry mass
t:	Drying time (h)
n:	Drum speed (min^{-1})
m, b:	Constants.
RG:	Rye Grass.
WC:	White Clover.
WCL:	White Clover Leaves.
WCS:	White Clover Stems.
k:	Constant in drying equation.
T:	Temperature (°C)
Suffix 15:	Corresponding to 15 rev min^{-1}
Suffix 20:	Corresponding to 20 rev min^{-1}
Suffix 30:	Corresponding to 30 rev min^{-1}
Suffix T.L.:	Corresponding to Thin Layer drying.

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6 AERODYNAMIC PROPERTIES OF COMPONENTS OF FORAGE FOR HAY PRODUCTION

6.1 ABSTRACT

Forages and herbs are composed by leaves and stems that have different drying times, and this complicates the management of product quality. Since their separation during drying could be made by an air stream, an evaluation of some aerodynamic properties of the components in relation to moisture content was made. Terminal velocity, unit density, and projected area of the components of white clover and ryegrass were tested. A test stand was used to determine terminal velocity, immersion was used for the unit density, and photography was used for the projected area. Terminal velocity was in the range 1.0 to 2.0 for clover leaves and 2.0 to 4.0 for clover stems and ryegrass, and Reynolds number was in the range 1000 to 5000 for clover leaves and 5000 to 35,000 for clover stems and ryegrass. The results showed better separation of components at high moisture contents.

Keywords. Aerodynamic properties, Forage drying, Hay, Terminal velocity.

6.2 INTRODUCTION

Drying composite materials is a common practice in the processing of grass for animal feed, herbs, aromatics, and medicinal plants, among other uses. Rotary drum drying uses air at high temperatures, in which the rotation and the air stream move the material along the cylinder and dry it. With this method, it is not easy to avoid under-drying and over-drying of the stems and leaves, respectively [6.1]. Loss in overall quality is associated with over- and under-drying. Over-drying results in crumbling during or after the process, while under-drying is associated with fungal spoilage.

The drying process is influenced by water movement within the plant and by external factors that can accelerate or slow the drying, [6.2]. In rotary drying, the conditions under which the drying time differences between components could be reduced are still uncertain. According to [6.3], energy can be saved if the dried parts are extracted from the dryer.

Three methods of component separation for the fractional drying of alfalfa have been discussed, [6.1]. (1) Separation while fresh before drying at high temperature and then recombining, (2) scalping of the chop over a shaking screen, and (3) separation of leaves from stems during harvest. [6.4] described a vertical perforated rotated drum and a horizontal air stream separator, using aerodynamic-based component separation. Further research for the optimum conditions for separation in rotary drying of grass for hay has been recommended, [6.3].

The objective of this research was to characterize the moisture content dependent variation of the key aerodynamic properties of the components of a mixture of white clover and ryegrass.

It was assumed that differences in terminal velocity, drag coefficient, and Reynolds number between the leaf, stem, and plant components of a grass mixture could be used to separate these components, based on variation in their moisture contents during drying.

6.3 THEORY

The interaction between a particle and the fluid in which it falls is affected by its density, shape and size, the density and viscosity of the fluid, and the relative velocity between them. [6.5] mentioned that the terminal velocity and aerodynamic drag resistance can be determined in the laboratory using the drop method or the suspension method. In the drop method, which is useful for small particles, a body is left to fall in the fluid from certain height until it reaches a constant speed, and a distance versus time plot is then used to compute the terminal velocity. In the suspension method, the terminal velocity corresponds to that which is just enough to keep the body suspended in a vertical airflow, [6.5]. This method has been applied for large particles, such as straws and stems, but the main difficulty has been the possible rotation of irregularly shaped objects and maintaining stable flotation, [6.6].

When the weight of a particle is equal to the fluid drag force, the particle remains suspended in the fluid, [6.7], and the terminal velocity can be determined as:

$$m_p \cdot g \left[\frac{\rho_p - \rho_f}{\rho_p} \right] = \frac{1}{2} C \cdot A \cdot \rho_f \cdot V_t^2 \tag{6.1}$$

Since $m_p . g = w$:

$$V_t = \left[\frac{\rho_p - \rho_f}{C \cdot A_p \cdot \rho_f \cdot \rho_p} \right]^{\frac{1}{2}} \tag{6.2}$$

$$C = \frac{2w\left(\rho_p - \rho_f\right)}{V_t^2 \cdot A_p \cdot \rho_f \cdot \rho_p} \tag{6.3}$$

[6.8] showed that the resistance factor (*k*) in equation 6.5 is better for terminal velocity characterization than the drag coefficient (*C*) because it is not dependent on the projected area of the particles.

When the particle moves in the fluid:

$$\frac{dv}{dt} = g\left(1 - \frac{k}{m \cdot g} \cdot V^2\right) \tag{6.4}$$

If the body has reached terminal velocity ($dv/dt = 0$):

$$k = \frac{m \cdot g}{V^2} \tag{6.5}$$

6.4 MATERIALS AND METHODS

6.4.1 Vegetal Material

For this study, white clover and ryegrass were collected from a hay field in Eichenberg, Germany. The samples were collected in June 2010, before the flowering stage, at heights of about 50 and 20 cm for white clover and ryegrass, respectively. The material was stored for 24 h before drying and was then separated into ryegrass and white clover, while the white clover was further separated into sets of single leaf, three leaves, stems, and the entire chop of white clover, where the term “chop” refers to a white clover component formed by a single stem and its three conjunct leaves. Samples (1000 g) of each of these sets were dried in a thin layer in a convection oven at 60°C, and 100 g were randomly extracted from the drying batch every 15 min until the minimum moisture content (χ) was reached (table 6.1).

Table 6.1. Moisture content (χ, g water g^{-1} dry mass), unit density (ρ_u, g cm^{-3}), length (*L*, cm), and area (*A*, cm^2) of the mixture components.

Drying Time (min)	Ryegrass			White Clover			White Clover Leaves				White Clover Stems		
									Single Leaf	Three Leaves			
	χ	ρ_u	*L* (cm)	χ	ρ_u	*A* (cm^2)	χ	ρ_u	*A* (cm^2)	*A* (cm^2)	χ	ρ_u	*L* (cm)
0	5.76	0.65	19.0 ±2.9	2.94	0.83	25.1 ±10.7	2.76	0.415	7.2 ±2.5	26.3 ±9.6	3.68	0.72	15.2 ±9.2
15	3.15	0.46	16.2 ±6.7	2.67	0.81	18.0 ±5.0	2.14	0.36	8.9 ±4.2	16.3 ±6.8	3.09	0.67	23.9 ±8.1
30	2.20	0.36	14.1 ±5.5	2.15	0.77	15.8 ±4.7	0.80	0.32	3.0 ±0.5	10.2 ±3.7	1.12	0.45	14.1 ±4.5
45	0.37	0.34	27.4 ±8.2	0.47	0.56	7.1 ±3.1	0.19	0.35	3.3 ±0.8	3.7 ±1.1	0.52	0.36	6.2 ±6.2
60	0.07	0.36	10.8 ±3.5	0.13	0.50	7.7 ±2.6	0.09	0.36	9.2 ±2.2	4.6 ±1.0	0.22	0.31	13.1 ±4.4
75	0.02	0.34	22.0 ±6.0	-	-	-	0.06	0.36	6.8 ±2	3.6±0.6	-	-	-

6.4.2 Density and Moisture Content Determination

The unit density (ρ_u) of the samples was measured by immersion in distilled water. Before weighing, a fine brush was used to cover the parts with a thin film of mineral oil to avoid water absorption. For each component and moisture content, three randomly selected samples were used. The weight of a 100 mL volumetric flask was measured when empty. The flask was then filled with distilled water at 20°C up to its graduation mark and weighed again. Each individual sample was placed in the empty flask, which was then filled with distilled water until a little below the mark. The sample was stirred in the water using a glass rod to remove air bubbles. Finally, the flask was filled up to its graduation mark and then reweighed. Using the difference between these weights and the density of distilled water, the unit density of the sample was obtained. This procedure was adapted from [6.9] used on cubes, pellets, and crumbles, in which a wax cover is reported. The moisture content of the samples was determined following the method in [6.10]. The moisture content, unit density, and area or lengths of the samples are shown in table 6.1.

6.4.3 Projected Area Determination

For determination of the aerodynamic properties, the projected area of the particles is required. For each component (single leaf, three leaves, clover stems, clover chop, and ryegrass) and each moisture content, 100 g was separated randomly, from which 15 samples were randomly selected. The samples were numbered and spread over a sheet of white paper with a square mesh of thin lines of known spacing, taking care to avoid overlapping, and then photographed. The projected areas were measured with ImageJ software [6.11]. In this software, the mesh is calibrated manually by putting a line of known length on the grid, and then its length in pixels is matched to the actual length in mm. The image was converted into binary black and white, and then each particle was individualized with the selection tool and its area determined with the software measurement tool.

6.4.4 Terminal Velocity Determination

The previously selected samples were also used for measurement of terminal velocity. A vertical duct of 400 mm diameter and 1000 mm length was used. Under the duct, a straightener section with a layer of two fine wire meshes and a honeycomb grid was used. The airflow was controlled with a butterfly valve behind an axial fan (figure6.1).

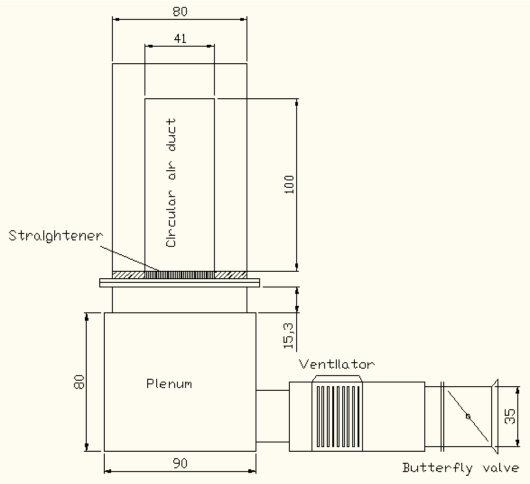

Figure 6.1. Device used for terminal velocity measurement. (Sizes in cm).

For the test, the particles were dropped down in the upper part of the vertical duct while the air was blowing up. The airflow was adjusted using the butterfly valve during some trials until equilibrium suspension was achieved. The terminal velocity was then measured with a micro-anemometer with a precision of 0.1 ms^{-1}, with its sensor positioned at the center of the column at the height of the floating particles.

The clover stems and ryegrass did not maintain a stable orientation in the air stream. [6.12] mentioned that stability depends on the location of the node. For this reason, the two ends of every clover stem and every ryegrass piece were joined together with a little paper tape (weighing less than 1% of the sample) in order to form a circle that could maintain a stable position in the air stream and also project the largest area corresponding to the total length of the sample. The clover leaves were analyzed individually and as natural conjuncts of three leaves. In the same way, the complete chops of clover and of ryegrass were also analyzed against the air stream.

6.5 RESULTS

6.5.1 Terminal Velocity and Weight-to-Area Ratio

Figure 6.2 shows the variation in the weight-to-area (*w*/*A*) ratio and the area (*A*) of the particles as a function of moisture content. As the drying advanced, a reduction in the projected area of the leaves was observed, which can be attributed to curling and hardening, especially in the driest states. For single leaves, the area reduction was 54% on average from the fresh to dry states. For the three conjunct leaves, this reduction was 86%, which is attributable to the sum of the individual reductions. The single stems experienced an average reduction of 51%, leading to a total reduction in the clover chop of 69.5%. The ryegrass had an average reduction of 82% in projected area.

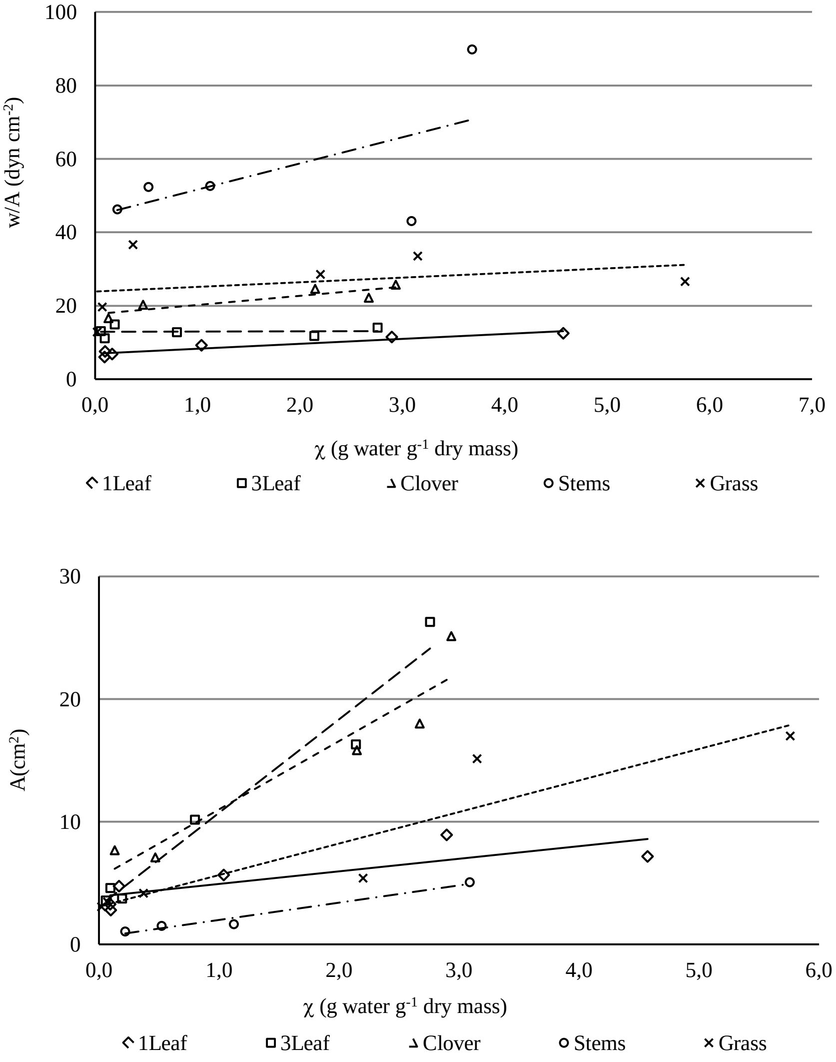

Figure 6.2. Changes in weight-to-area (w/A) ratio and area (A) with the moisture content (χ).

Figure 6.3 shows the transition in shape between the fresh and dry states, and figure 6.4 shows the relationship between the *w*/*A* ratio and terminal velocity (V_t) of the components at different moisture contents. A linear relationship was deduced at most of the moisture contents of the form:

$$V_t = a\frac{w}{A} + b \tag{6.6}$$

[6.13] also reported a linear relationship between V_t^2 and weight for three ranges of moisture content for the leaf fraction and stalk fraction of chopped corn silage.

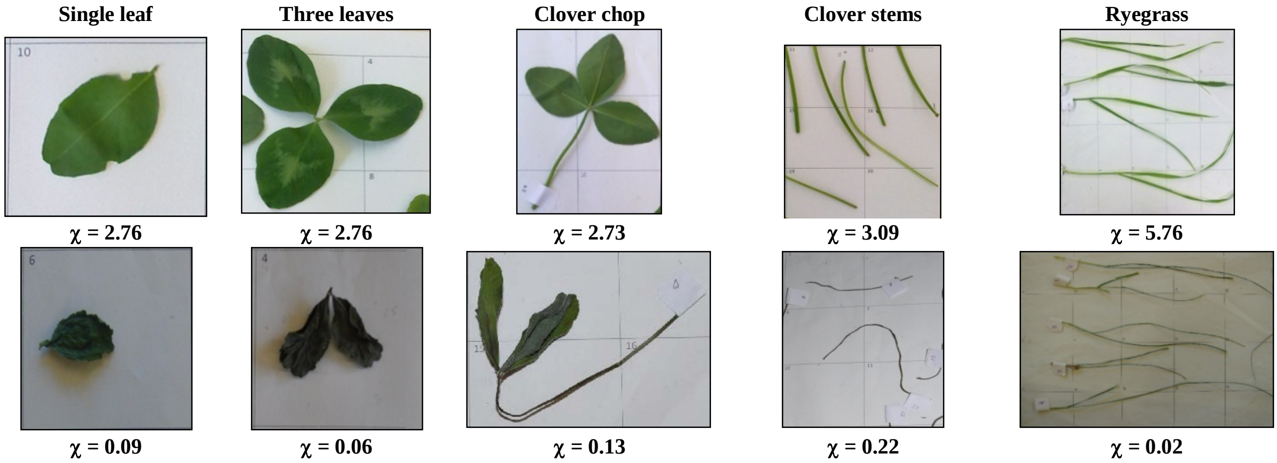

Figure 6.3. Change in shape between the fresh state and the driest state. (χvalues in g waterg^{-1} dry mass).

6.5.1.1 Single Leaf

Figure 6.4 shows that the lines were almost parallel in the regressions for $\chi < 0.19$, with slopes (coefficient *a* in eq. 6.6) between 10.6 and 12.2 and R^2 values between 0.65 and 0.87. This is consistent with the small variation in the unit density at these χ values. For the fresher states, the linear relationship was weaker, which is probably due to the variation in unit density of the samples.

The data shift to the left as χ decreased. This could be due to the loss of weight and the area reduction of the leaves with drying. However, the terminal velocity was observed to cover a similar range (between 0.5 and 1.6 m s^{-1}) for each χ value. These values of V_t are lower than those reported by [6.13] who found a reduction in terminal velocity from 3.9 to 5.16 m s^{-1} for leaves of chopped corn silage when the moisture content decreased from the range of 0.6 to 0.7 g water g^{-1} dry mass to the range of 0.4 to 0.5 g water g^{-1} dry mass. The results are consistent with the findings of [6.8], who reported an average V_t of 1.2 m s^{-1} for alfalfa leaflets with petioles and triple leaflets with petiole in the fresh state.

The results showed that V_t decreased as χ decreased (fig. 6.4). One ANOVA, with moisture content as factor, showed that χ had a big effect on the variation of V_t. A Duncan test showed, with 99.5% confidence, that V_t in the fresh state was higher than with the other values of χ, and V_t was lowest at $\chi = 0.8$. There were no significant differences between the other values of χ.

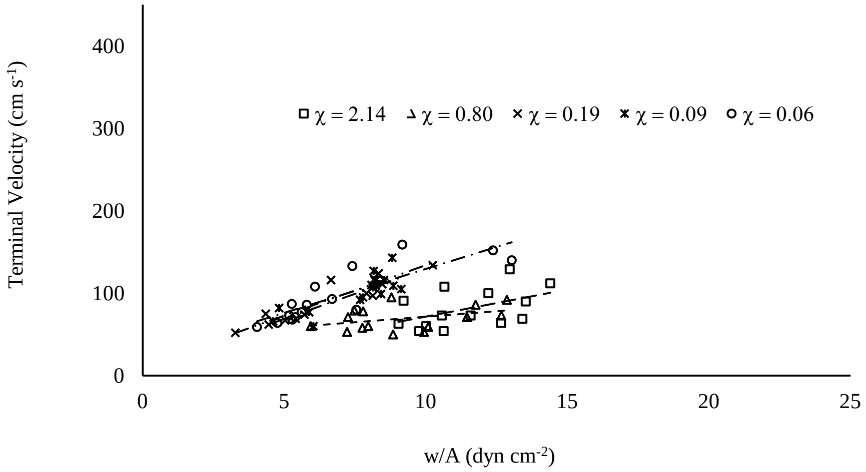

Figure 6.4. Relationship between terminal velocity (V_t) and *w/A* ratio, for Single leaf. χ (g water g^{-1} dry mass)

6.5.1.2 Three Leaves

For all moisture contents, coefficient *a* (eq. 6.6) varied between 3.8 and 11.5, while coefficient *b* varied between 10.9 and 82.0. The best fit of equation 6.6 was for $\chi < 0.80$, with an R^2 value between 0.709 and 0.890. Figure 6.5.

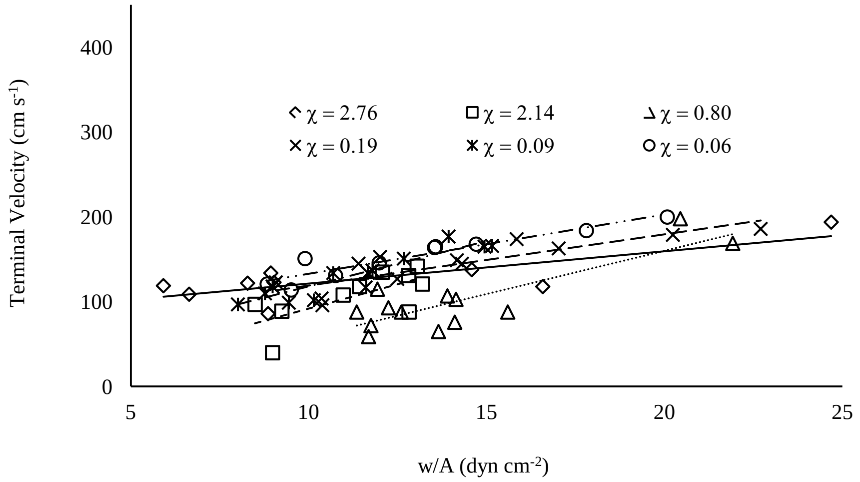

Figure 6.5. Relationship between terminal velocity (V_t) and *w/A* ratio. For Three Leaves. χ (g water g^{-1} dry mass)

For three leaves, the data also shifted to the left as χ decreased, which meant that in general V_t decreased as the material lost moisture. However, no significant variation between V_t with χ was observed. This can be explained because the range of *w/A* is similar for the several χ values.

A comparison of means showed, with 99.5% confidence, that there were no significant differences in V_t because of χ. A Duncan comparison also showed insignificant differences in V_t for χ between 2.76 and 0.8 and for χ between 0.19 and 0.06. [6.13] reported similar trends for all the particles of chopped corn silage.

6.5.1.3 Clover Stems

Although there were differences in the behavior of the terminal velocities at several χ values, a relationship between V_t and the *w*/*A* ratio for each χ was not found for clover stems.

For the fresh state, the terminal velocities were a little higher than for the driest state. With 99.5% of confidence, it can be affirmed that there were differences in terminal velocity due to χ. The Duncan and Tukey tests showed that there were no similarities between V_t at the χ values studied. This could account for the large reduction in the *w*/*A* ratio with drying. The average V_t was 3.37, 2.44, 2.16, and 1.72 m s^{-1} for χ values of 3.68, 1.12, 0.52, and 0.22 g water g^{-1} dry mass, respectively. Figure 6.6.

[6.8] found a relationship between V_t and the weight of alfalfa stems at several lengths with the node in the middle, at one end, and without the node. For the range of stem weights in the present research, and using the relationships from [6.8], the V_t for clover stems should vary between 2.89 and 20.19 m s^{-1}. This study obtained V_t between 1.72 and 3.86 m s^{-1} for the dryer and fresh states, respectively, which corresponds (in 6.8) to lengths between 7.5 and 10 cm and the node in the middle of the stem. These results are also in the range for node-free wheat straw with lengths between 8 and 10.4 cm reported by [6.12].

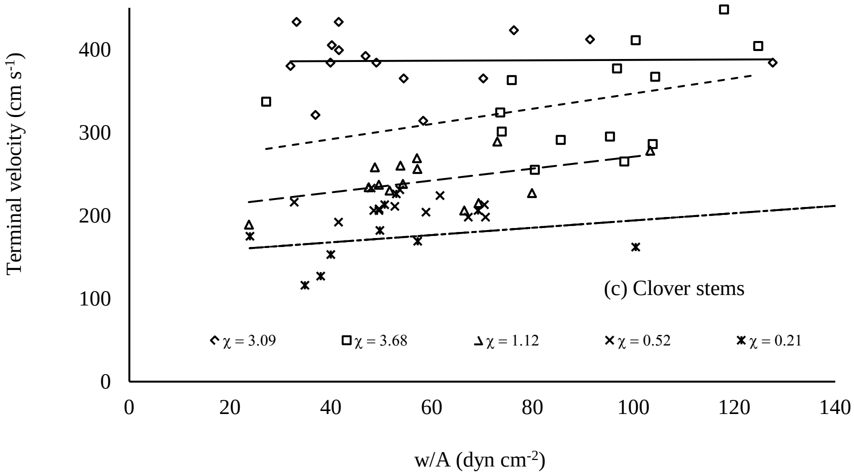

Figure 6.6. Relationship between terminal velocity (V_t) and *w*/*A* ratio. Clover Stems. χ (g water g^{-1} dry mass)

These similarities could be explained because the stems were shaped into a ring with its face against the airflow, as in the case of the middle node stems of [6.8] and the node-free straw of [6.12], which avoids the necessity of measuring the projected oblique area of the material.

6.5.1.4 Ryegrass

Like the other components of the mixture, decreasing the *w*/*A* ratio caused a reduction in V_t for ryegrass, which led to a linear relationship (eq. 6.6) at all χ values. In this case, the range of *w*/*A* was different between moisture contents: when χ was under 0.1, *w*/*A* had values between 8.5 and 27 dyne cm^{-2}, while when χ was close to fresh, *w*/*A* varied between 7 and 75 dyne cm^{-2}. Figure 6.7.

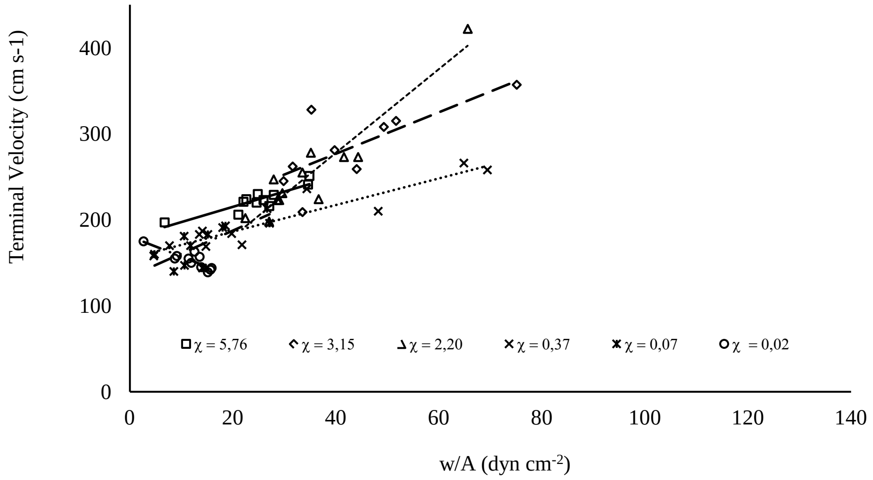

Figure 6.7. Relationship between terminal velocity (V_t) and *w*/*A* ratio. For Ryegrass. χ (g water g^{-1} dry mass)

For ryegrass with χ between 5.76 and 0.07, coefficient *a* in equation 6.6 varied from 1.55 to 4.86, and coefficient *b* varied from 83.10 to 180.50. In the case of χ = 0.02, *a* was -2.32 and *b* was 136.9. These relationships had R^2 values between 0.61 and 0.87. In a general case considering all the data, coefficient *a* was 2.94 and *b* was 136.9, with R^2 of 0.729. The slopes of the regression lines (fig. 6.4d) were steeper for ryegrass than for the other components of the mixture because of the high area reduction.

The ryegrass was also shaped into a ring by joining the two extreme ends. In many cases, one or more leaves floated freely in the airstream and perpendicular to the ring, so that the area facing the airflow was that of the ring. In other cases, the main face of the ring was parallel to the air stream, and the area facing the flow corresponded to the diameter of the ring multiplied by the thickness of the grass sample.

6.5.1.5 Clover Chop

The analysis of the clover chop was more complex because it had a composite geometry of leaves and stems. In general, the performance in the fresh state was different from the other states. In the fresh state, V_t was almost five times higher than when the material had lost 25% of its moisture content. It was also observed that the fresh tissues were turgid, and the leaves experienced little deformation with the passage of air. At lower moisture contents, the leaves bent in the direction of the airflow, partially covering the stems. Figure 6.8.

An R^2 value of less than 0.65 was obtained for the relationship between the *w*/*A* ratio and V_t at all moisture contents, indicating no significant linear relationship. However, it was evident that V_t increased with an increase of the *w*/*A* ratio, and this increase was consistent for all moisture contents.

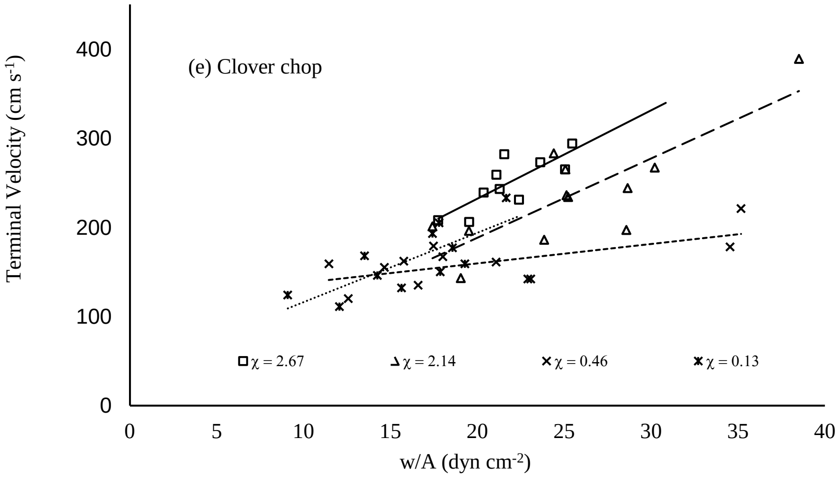

Figure 6.8. Relationship between terminal velocity (V_t) and *w/A* ratio. Clover Chops. χ (g water g^{-1} dry mass)

6.5.2 Airflow Characteristics.

An analysis of the air flow regime required to reach terminal velocity of the particles was made. In all cases, a linear relationship between Reynolds number (Re) and the weight (*w*) or length (*l*) of the material was found.

6.5.2.1 SingleLeaf.

The *w*-Re relationship was almost the same at $\chi< 0.19$. At high χ, it followed quasi-parallel lines and changed for each χ (fig. 6.5a). Re varied between 500 and 4000, which is in accordance with [6.7] and corresponds to the beginning of turbulent flow. For χ between 2.14 and 0.8, Re varied between 790 and 3780. For dry leaves, with χ between 0.19 and 0.06, Re varied between 605 and 2595. Although the whole range belongs to the turbulent regime, tendencies to laminar flow were observed for small and dry leaves.

Because the unit density (ρ_u) is the same for each χ level, the Re of each sample varied only with the projected area, which was a function of its weight (fig. 6.9). This accounts for the similar behavior of the leaves at the driest states, which experienced small changes in their *w/A* ratio during drying.

Although there were mostly linear tendencies, there were also some scattering in the data for Re around 1500 at all the moisture contents. This could be explained by turbulence in the boundary layer and changes in the effective drag area caused by the particle behavior [6.8].

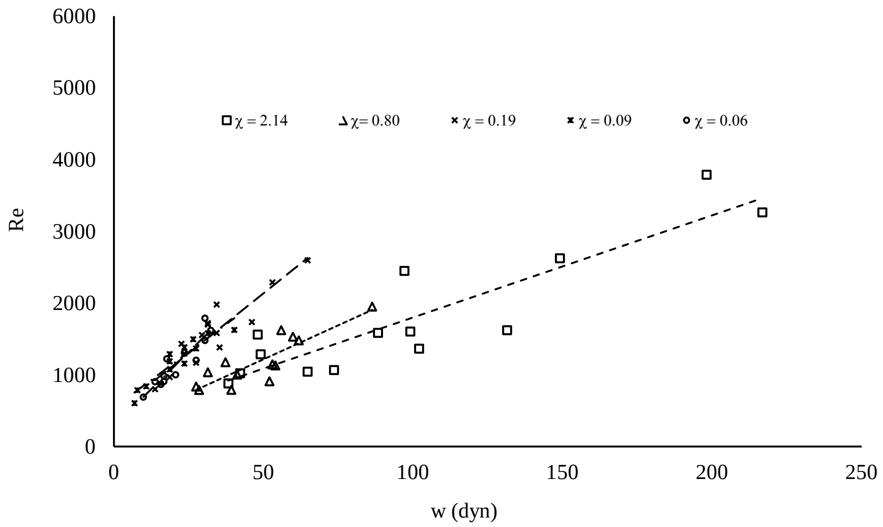

Figure 6.9. Reynolds (Re) as function of weight. Single Leaf.
χ (g water g^{-1} dry mass)

6.5.2.2 Three Leaves

As in the case of the single leaf, Re decreased with χ (fig. 6.10) for three leaves, but particles with the same projected area were observed to share the same range of Re.

At low χ, the range of Re was comparatively less than at high χ, which indicates some stability of Re, as laminar flow was reached, and more instability when the leaves were fresh and the flow tended to be turbulent. Similarly, at $\chi = 0.2$, the maximum Re was 50% of the corresponding fresh state value.

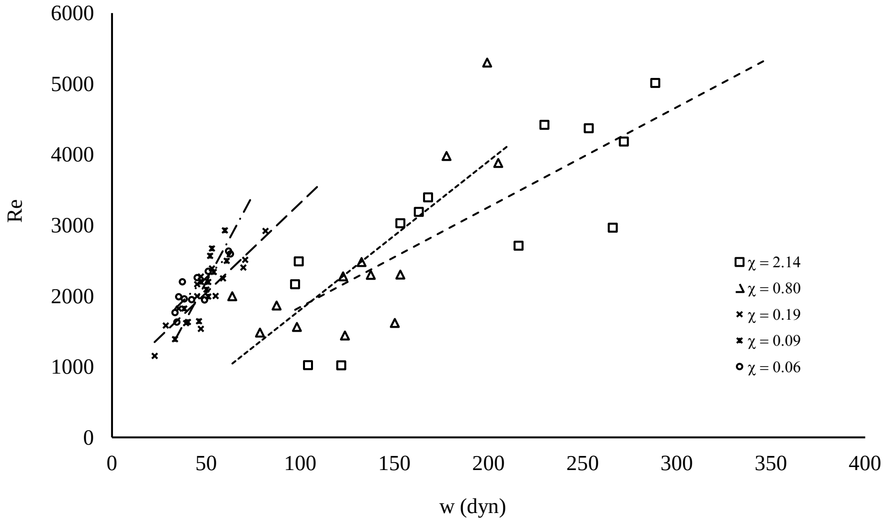

Figure 6.10. Reynolds (Re) as function of weight. Three Leaf.
χ (g water g^{-1} dry mass)

Depending on the moisture content, two linear relationships were observed (fig. 6.10): for $\chi>0.8$, the slope was 0.82 with a constant of 466; for $\chi< 0.19$, the slope was 27.8 with a constant of 765.7.

6.5.2.3 Clover Stems

A linear correlation was found between Re and the length of the stems, (fig. 6.11). In the evaluation of Re, the total area of each stem was used, since each stem was set as a ring facing the air stream. Re tended to increase as the length of stems increased, with the regression lines being almost parallel for each moisture content.

For the determined linear correlations ($Re = h + j.l$), the R^2 values were between 0.78 and 0.94. For $\chi < 3.10$, *h* was between 834 and 869, while *j* was between -1423 and -1900. For $\chi < 1.12$, *h* varied between 336 and 571, while *j* varied between -798 and -2223.

Re was highest for the fresher states, even for similar stem lengths, due to the change in the *w*/*A* ratio. For the fresh stems, Re varied between 29000 and 96000. For χ between 1.12 and 3.09, Re varied between 13000 and 46000. For χ between 0.2 and 1.12, Re varied between 8000 and 22000.

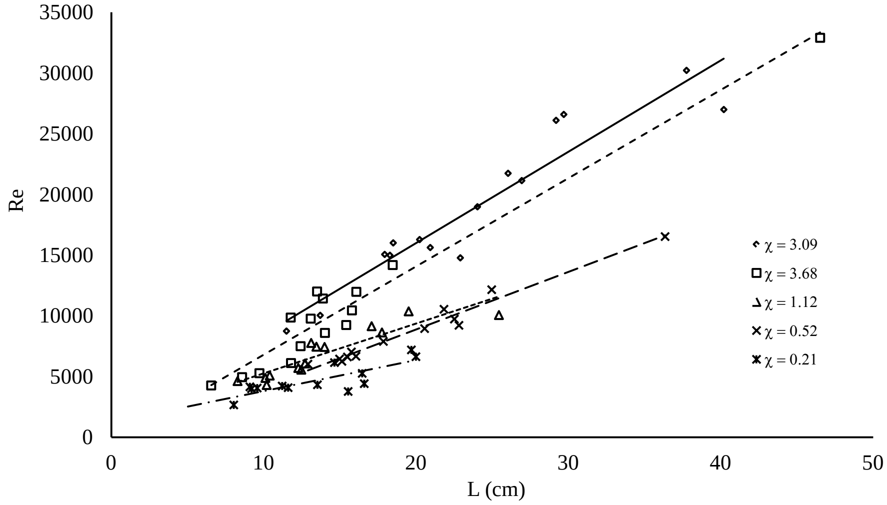

Figure 6.11. Reynolds (Re) as function of Length. Clover Stem.
χ (g water g^{-1} dry mass)

The Re values obtained in this study are higher than those of [6.12], who obtained Re values between 1324 and 2699 for wheat straw particles with lengths between 8.5 and 36.5 mm. However, the present results are in the range of those reported by [6.8], who obtained Re values between 2570 and 25900 for alfalfa stems with lengths between 6.35 and 101.6 mm.

For clover stems, the Re and length relationship did not show any deviation from the linear tendency because of the stability of the rings in the air stream at terminal velocity.

6.5.2.4 Ryegrass

An apparent linear relationship between Re and weight (*w*) was found for ryegrass, but a mathematical relationship could not be established because of data dispersion. This may be because the ryegrass had leaves of different lengths, which assumed different orientations in the airflow. When Re was calculated using the area of the maximum length of the pieces of ryegrass, a linear relationship was found (fig. 6.12), which varied with moisture content. These lines are not parallel because two samples of ryegrass could have had the same length but a different *w*/*A* relationship at the same χ, therefore yielding different terminal velocities.

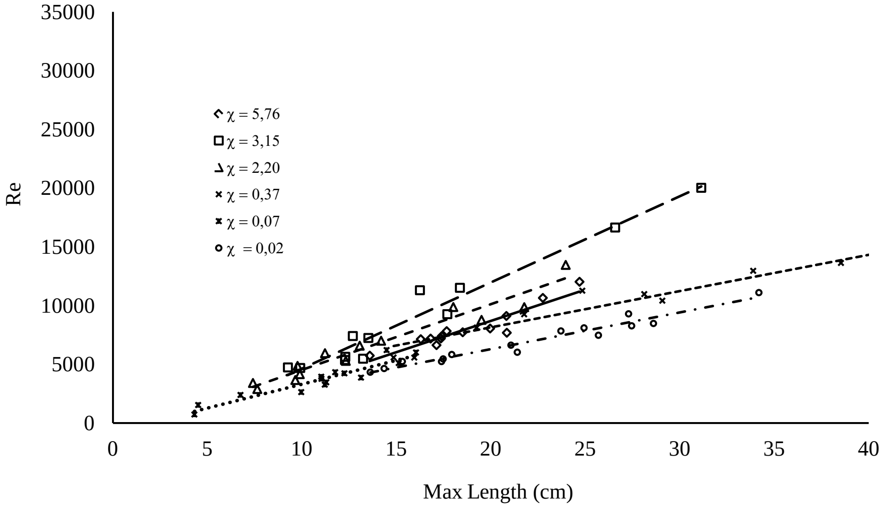

Figure 6.12. Reynolds (Re) as function of Max. Length. Ryegrass. χ (g water g^{-1} dry mass)

For each χ, a small range of Re was found, which generally varied between 700 and 20000 for lengths between 4 and 34 cm. For the fitting of the relationship Re = $h + j.l$, the R^2 value was between 0.87 and 0.96. For $\chi < 2.2$, h varied between 1075 and 2707, and j varied between 530 and 733. For $\chi < 0.02$, h varied between 57 and 1971, and j between 308 and 407.

6.5.2.5 Clover Chop

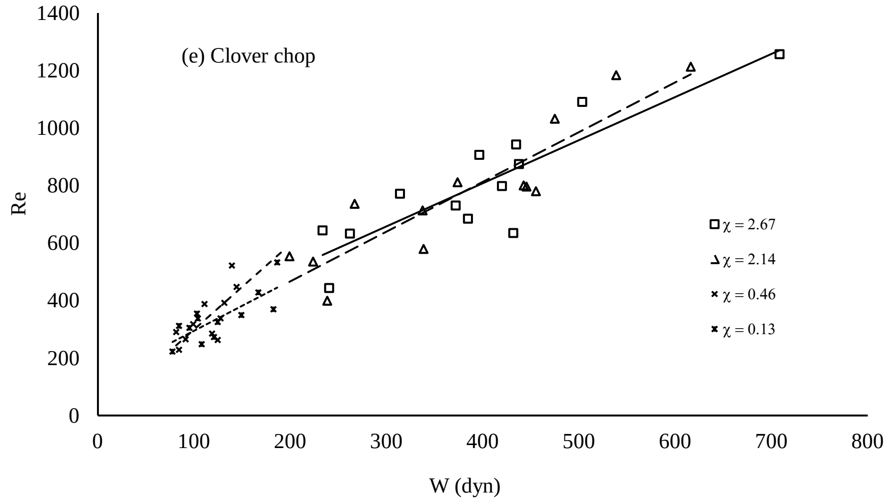

Figure 6.13. Reynolds (Re) as function of Weight. Clover chop. χ (g water g^{-1} dry mass)

For the complete chop, there was a linear relationship between Re and weight (fig. 6.13), and these lines were almost parallel for every χ. It is interesting that for the range of χ, Re was less than that corresponding to the three leaves or to the stems, although the *w*/*A* ratio for three leaves was a little less than that for the chop. In the chop, the projected area facing the air was a fraction of the conjunct of the three leaves. This reduction of area was due to the presence of the stem, which caused the leaves to bend more. In the fresh state, the Re of the chop was 20% less than that of the three leaves. At χ= 2.14, it was 75% less, while at χ= 0.09, it was 84% less.

The fresh material covered a wider range of weights. For $\chi < 0.46$, the w-Re relationship was very similar, and the range of weights and Re was less. Except for $\chi = 0.46$, the slopes of all lines were between 1.5 and 1.7, and the cutoff varied between 120 and 207, suggesting parallel lines, and thus the moisture content did not alter the Re-w relationship. A relationship considering all χ is $1.6685w + \text{Re} = 140.86$ ($R^2 = 0.9138$), which was valid for weights between 77 and 710 dyne (80 to 720 mg).

6.5.3 Drag Coefficient

The drag coefficient (C) was related with Re for each moisture content of the mixture components. Potential relationships were found for all components except clover stems, for which a linear relationship between Re and k was found.

6.5.3.1 Single Leaf

There was a relationship of the form $C = m.\text{Re}^n$ at each χ (fig. 6.14), whose constants are listed in table 6.2 for the fresh, middle, and dry states. Using the linear relationship between the projected area and the weight of the leaves and the average values of C and k at every χ, a relationship was estimated between the terminal velocity and the w/A ratio (fig. 6.15).

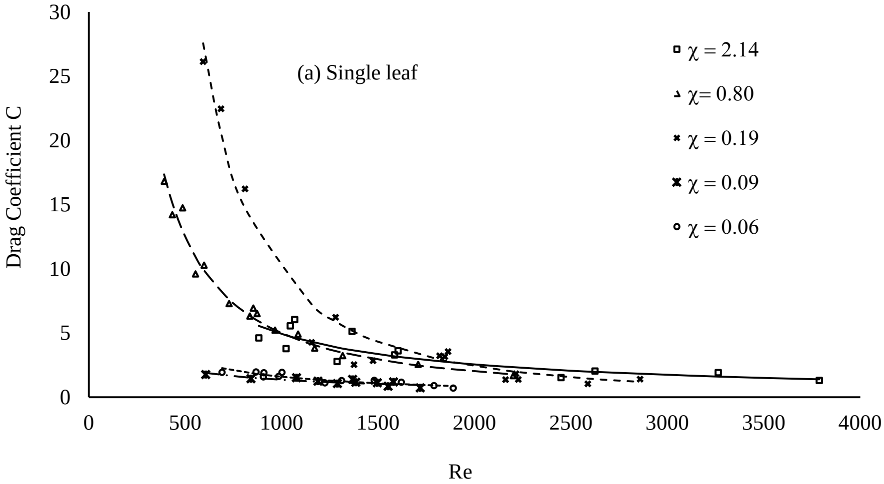

Figure 6.14. Drag coefficient (C) as a function of Re. Single Leaf. χ (g water g^{-1} dry mass)

As figure 6.14 suggests, there are two variations in the function of χ: for $\chi < 0.09$, there were similar values of C; for $\chi > 0.19$, C was high for low weight (low Re) and low for high weight (high Re).

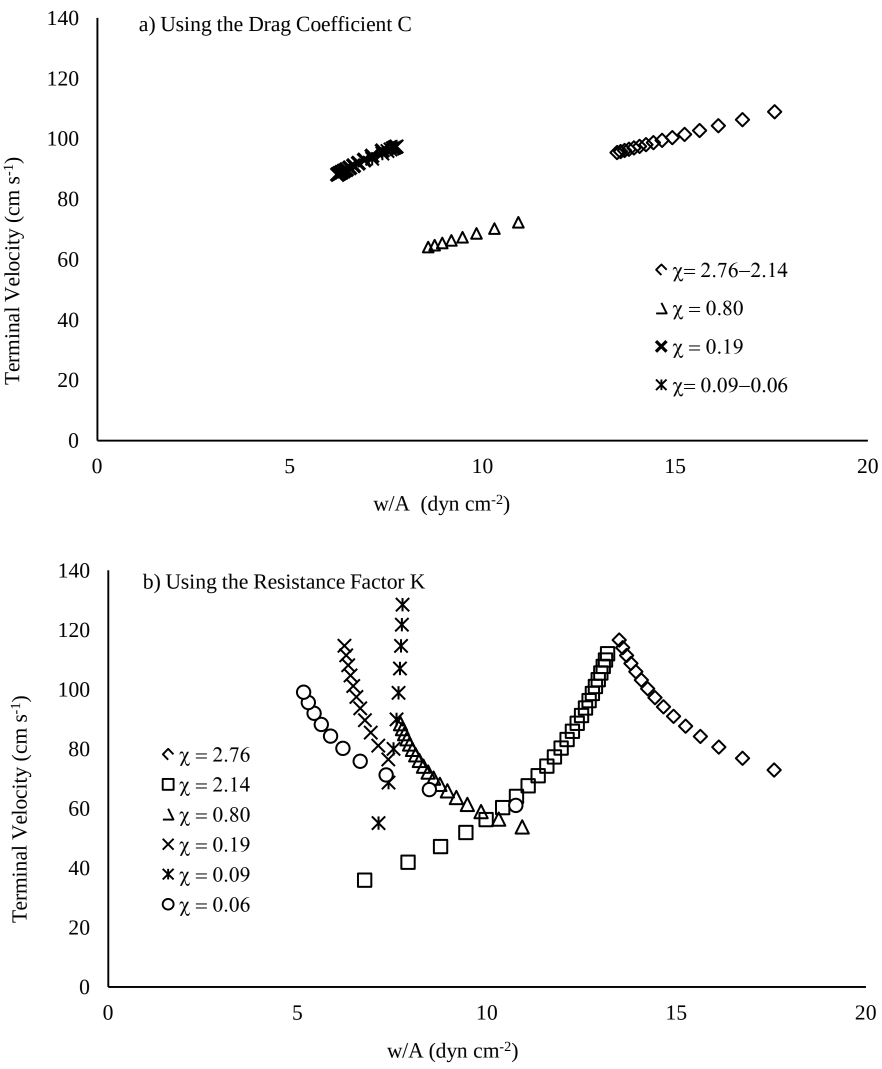

Figure 6.15. Estimated terminal velocity for single leaves.
χ (g water g^{-1} dry mass)

There was a contrast in the trends of the terminal velocity at different moisture contents when *C* or *k* was used for the calculation. With the drag coefficient (*C*), there were some similarities between the high χvalues and between the low χ values. With the resistance factor (*k*), these similarities were less evident, and there was more variation in the estimated velocity for the same χvalue than there was in the real data.

Figure 6.16 shows the evolution of the resistance factor (*k*) as a function of χ for all the components of the mixture. A decreasing linear tendency of *k* with moisture content was found. The decrement was more intense for the leaves and much less for ryegrass, stems, and clover chop (for which it was more constant).

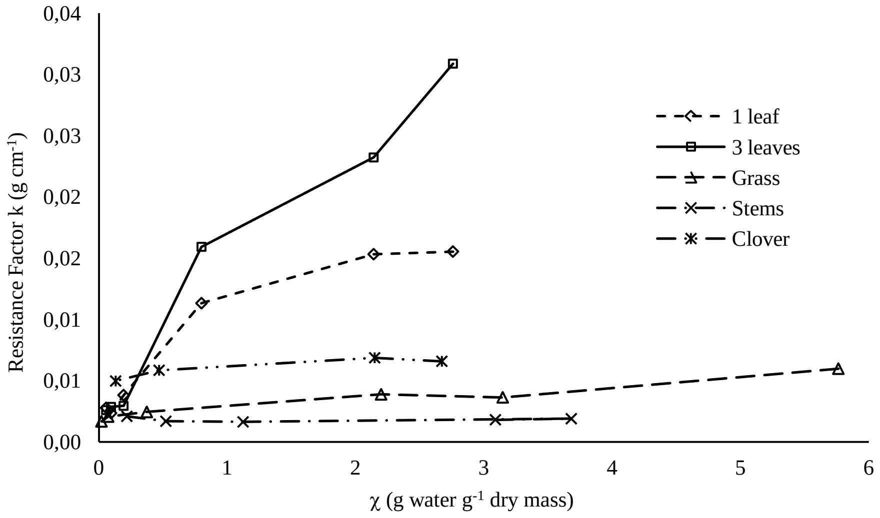

Figure 6.16. Evolution of constant *k* with reduction in χ for all components of the mixture.

6.5.3.2 Three Leaves

The three leaves showed similar tendencies as single leaf. The variation in *C* decreased with χ (fig. 6.17). There were two variations in the *C*-Re relationship as a function of χ: for χ between 0.06 and 0.8, *C* varied between 0.55 and 1.6; for $\chi > 0.8$, *C* varied from 0.65 to 7.00.

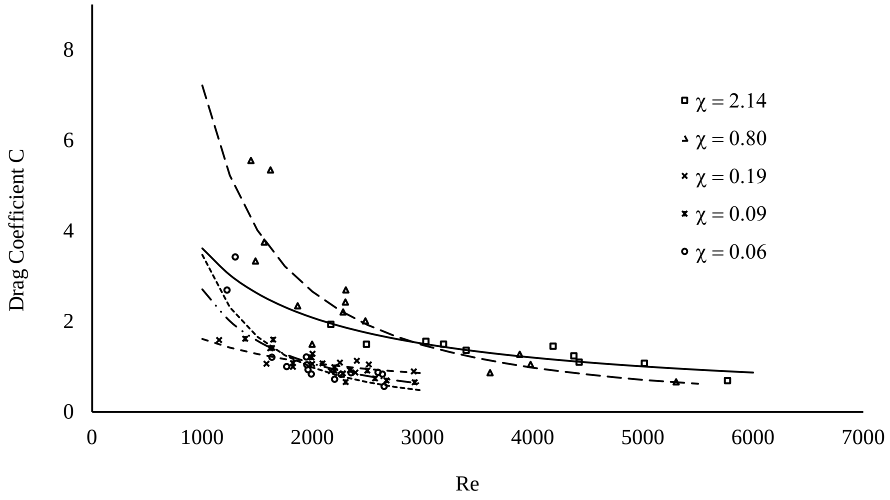

Figure 6.17. Drag coefficient (*C*) as function of Re. Three Leaves.
χ (g water g^{-1} dry mass)

For single leaf and three leaves, *C* increased rapidly for Re less than 2500 to 3000 and then increased slowly. Re values lower than these corresponded to samples with small *w*/*A* ratios in the driest states, or to small particles, for which the tendency was for laminar flow.

Samples with the same Re but different moisture contents had different drag coefficients. The difference was higher for the driest material and almost negligible for the fresher material. The values of the *C*-Re relationship are listed in table 6.2.

6.5.3.3 *Clover Stems*

For stems, the differences in *C* were smaller than for the other components of the mixture. Figure 6.18. Nevertheless, *C* tended to increase as χ decreased. The *C* variations were 0.29 to 1.33, 0.95 to 2.59, and 1.29 to 6.33 for the fresh state (χ = 3.68), intermediate state (χ around 1.12), and driest state, respectively. For all stems, the change in *C* with Re was more pronounced for Re between 1000 and 5000, and the change in *C* was smaller for Re up to 35000. These values of *C* are higher than those reported by [6.12], which were between 0.88 and 1.04 for Re between 1312 and 2792, and for shorter samples of straw. [6.8] found values of *C* in the range between 0.5 and 2.0.

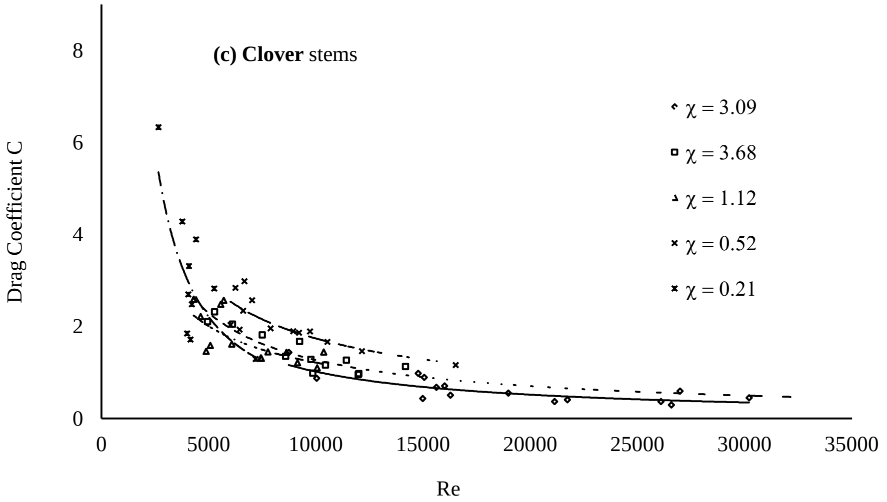

Figure 6.18. Drag coefficient (*C*) as function of Re. Clover Stems. χ (g water g^{-1} dry mass)

6.5.3.4 *Ryegrass*

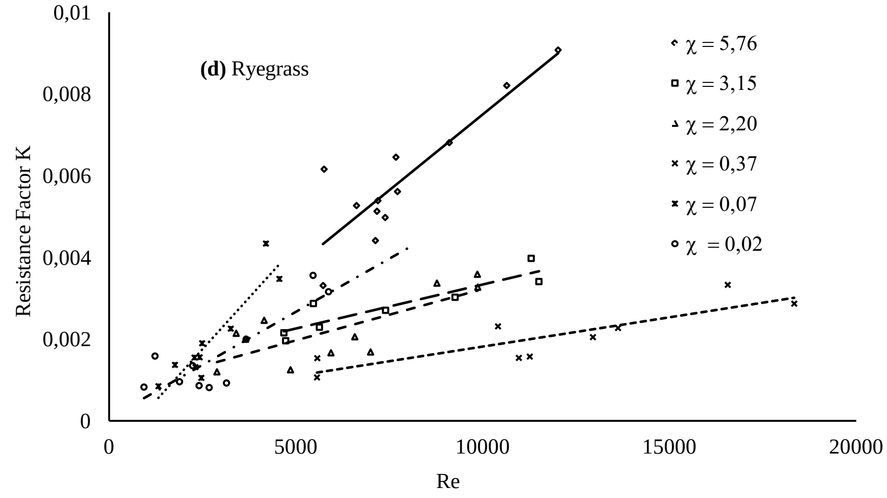

Figure 6.19. Drag coefficient (C) as function of Re. Ryegrass. χ (g water g^{-1} dry mass)

Unlike the other components in the mixture, it was not possible to establish a tendency or an approximate value for *C* with the variation of V_t and Re. A linear regression was obtained with the resistance factor *k*, as shown in figure 6.19 and table 6.2. Because of the nature of the test and the complexity of the ryegrass, it was considered better to use *k*, which is independent of the projected area of the sample. In general, a relationship between *k*, Re, and χ could not be determined.

6.5.3.5 Clover Chop

The *C*-Re relationship for clover chop is given in figure 6.20. It was found that for χ in the ranges of 2.67 to 2.15 and 0.46 to 0.13, the *C*-Re relationship was very similar. In this case, a single correlation for all χ could not be found, despite having equal Re, due to variations in the projected areas of the chop, which decreased with decreasing moisture content (fig. 6.20).

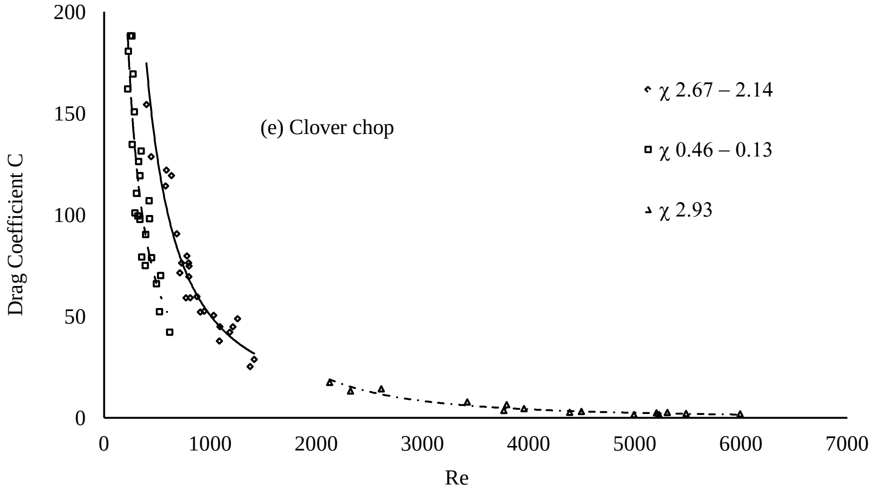

Figure 6.20. Drag coefficient (*C*) as function of Re. Clover Chop.
χ (g water g^{-1} dry mass)

For fresh clover chop, Re varied between 2000 and 6000, and *C* varied between 1.5 and 17.5. For the dry state, Re varied between 210 and 1400, while *C* varied between 25 and 190. The values of the *C*-Re relationship are listed in table 6.2.

Table 6.2. *C*-Re relationships for the components.

χ (g water g^{-1} dry mass)		Relationship	R^2
Single leaf	2.75	$C = 2E+11 \cdot Re^{-3.306}$	0.70
	0.80	$C = 47688 \cdot Re^{-1.327}$	0.99
	0.09	$C = 134.53 \cdot Re^{-0.666}$	0.64
Three leaves	2.76	$C = 4E+7 \cdot Re^{-2.027}$	0.92
	0.80	$C = 152709 \cdot Re^{-1.442}$	0.85
	0.09	$C = 28909 \cdot Re^{-1.343}$	0.86
Clover stems	3.68	$C = 2868 \cdot Re^{-0,838}$	0.89
	1.12	$C = 6148 \cdot Re^{-0,929}$	0.76
	0.21	$C = 127543 \cdot Re^{-1,256}$	0.75
Ryegrass	3.15	$k = 2E-7 \cdot Re + 0.0017$	0.83
	2.20	$k = 3E-7 \cdot Re + 0.0007$	0.59
	0.37	$k = 1E-7 \cdot Re + 0.0004$	0.74
	0.07	$k = 1E-6 \cdot Re - 0.0008$	0.85
Clover chop	2.93	$C = 2E+9 \cdot Re - 2.387$	0.92
	2.67 to 2.14	$C = 658047 \cdot Re - 1.375$	0.90
	0.46 to 0.13	$C = 242301 \cdot Re - 1.326$	0.79

6.6 CONCLUSIONS

Drying a mixture of white clover and ryegrass achieved a decrease in the w/A ratio of each of the components of the mixture. This was observed to have a greater influence on the terminal velocity and other aerodynamic characteristics, such as C, k, and Re, than that of the particle projected area alone.

The relationship between the Reynolds number and the weight or length of the particles varied linearly for each the moisture content. However, this was not the case when the data were consolidated because, although the projected areas were similar, the w/A ratio varied depending on the moisture content.

In the fresh state, the terminal velocity was found to be similar between single leaf and three leaves, and different for stems, clover chop, and ryegrass. However, at lower moisture contents, this difference was reduced. Terminal velocities in the fresh state were 1.50, 3.8, and 2.9 m s^{-1} for single and three leaves, clover stems, and ryegrass, respectively. Particles with low moisture contents had lower terminal velocities than fresh particles.

Turbulent flow regimes were observed for fresh states, and laminar flow was observed for the drier states. Drying resulted in weight loss, which reduced the terminal velocity, causing laminar flow. The flow regime was generally different for leaves, stems, and ryegrass. Leaves, either alone, in groups of three, or attached to the stem, required less turbulent airflow regimes compared to stems or ryegrass. Stems, ryegrass, and clover chop always responded to turbulent regimes.

For all components except for ryegrass, the drag coefficient (C) was better suited for determination of the suspension force as compared to the resistance factor (k).

In general, it can be concluded that, at all moisture contents, there were enough differences in the aerodynamic properties of the clover leaves, clover stems, and ryegrass to facilitate airflow-based separation of these components. These differences were more pronounced for the fresh state as compared to the dryer states. The findings of this study could be applied in the design and operation of airflow-based systems, such as rotary drum dryers, fluidized beds, and pneumatic transport.

6.7 SYMBOLS LIST

A: projected area normal to the fluid velocity (cm^2)
a, b: constants for the relationship of V_t and w/A
h, j: constants for the relationship of Re and l
m, n: constants for the relationship of C and Re
V_t: terminal velocity (cms^{-1})
w: weight (dyne)
ρ_f: fluid density
ρ_u: particle unit density
m_p: particle mass
g: gravity acceleration

C:	drag coefficient ($C = C_{friction} + C_{normal}$)
K:	resistance factor (gcm^{-1})
χ:	moisture content (g water g^{-1} dry mass)
ρ_b:	particle bulk density (gcm^{-3})
Re:	Reynolds number

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7 HAY COMPONENT SIEVING BY A ROTARY SIEVE WITH LIFTING FLIGHTS

7.1 ABSTRACT

With the aim of improve de drying of hay composed materials, the already dried parts must be extracted from the mixture to save energy and avoid quality problems. For this, a separation test of a mixture of leaf and stems of ryegrass and clover for hay was developed using a rotary sieve with lifter flights and the vegetal material at several moisture contents. The best separation results were found for the dried state and rotation speed of 2.1 sec^{-1}. The stems separation efficiencies were between 74 and 96%.

Keywords: rotary sieve, hay, leaves and stems separation, grass drying.

7.2 INTRODUCTION

Some agricultural materials composed by leaves and stems, like grass for animal feeding, herbs, aromatic and medicinal plants and others, require to be dried. For these materials, and with the same air condition, the drying time varies between species and components according to their initial moisture content, plant morphology, specie and age. This phenomenon has been reported for leaf and stem components of several plants: [7.1], [7.2] and [7.3] in Alfalfa; [7.4] in Tall Fescue and Perennial Ryegrass, [7.5] in White Clover, [7.6] in Jew’s mallow, spearmint and parsley herbs, [7.7] in Coriander.

According to [7.8], extraction of the already dried parts of these mixtures leads to energy saving and avoids the lacks of quality of the final product, because over drying results in crumbling during or after the process while under drying is associated to fungal spoilage.

For example, the separation between leaves and stems in alfalfa hay is very important because of their different concentration of protein and different drying rate.

Some trails for its separation are mentioned by [7.2]: Separation in fresh before the drying at high temperature and then a recombining; scalping over a shaking screen of alfalfa shops at 15% of moisture content; separation of leaves from the stems in the harvest for its fractional drying in the dryer.

To separate leaves and stems, some intent has been proved regarding drying. [7.9] and [7.10] report one vertical perforated rotating drum air stream separator and other outer or inner perforated rotating drum under air suction. With feed rates varying between 360 and 2160 kg h^{-1} reached separation efficiencies higher than 90% at the low feed rates. [7.10] reports one horizontal air stream separator for mixtures of alfalfa with a feed rate of 2300 kg h^{-1}, and separation efficiency between 48% and 76%.

[7.9] developed one Rotary Drum for drying and separating alfalfa, using the aero-dynamic properties of the material; with a feed rate between 40 and 105 kg h^{-1}, this device reached leaf separation efficiency between 69 and 76 %.

As another alternative for separation of leaves from stems in a mixture of grass, like Alfalfa or Clover with Ryegrass for hay, the use of a cylindrical sieve inside a rotary drum dryer is proposed here with the aim of making the separation and drying of such materials.

Other methods for the drying of materials such as Herbal Medicines and Tea at industrial scale include forced air methods such as Multitray and Louver- Type ovens, Conveyer Belt and Fluidized Bed dryers. For small pieces, Oven, drying house; tunnel, vacuum and fluidized bed dryers are used. Either heated air or ambient drying are reported, [7.11]. For the hay curing and preserving, the material can be crushed, cracked or abraded in field to make the stems dry faster, and then let to dry under the action of the air and sun. This requires between 3 to 5 days for the unconditioned plants, and between 2 to 4 for the conditioned ones, [7.12]. Then the pasture can be baled and dried in barns in order to reach lower final moisture content than that reached just with the field curing. [7.13]

Screening is widely used in industries for large scale separation and sorting according to sizes, shapes or resiliencies, of a large number of materials like minerals and metallurgical, grains, food and pharmaceutical, [7.14], [7.15]. Such classification has been made by devices like rotating discs, vibrations, inclined chute, inclined vibrating screen and rotating cylinder; or by the difference in descent speed of particles as a function of the particle shape over an inclined solid wall. [7.16].

In a bladeless rotating cylinder the particles lift up and go down against the cylinder wall and move toward the lower end. There they reach certain height which depends on their shape, density and friction, [7.17]. With blades the particles reach a highest position and, with a suitable geometry, the area covered in the cylinder is bigger as well as the agitation of the mixture, all of which could lead to a greater possibility of separation of the components. Among the different available flight geometries there are straight, 120° angled, right angled, extended circular and others, [7.18]. The Equal Horizontal Distribution flights (EHD) give a homogenous distribution over the horizontal diameter of the drum; the falling particles are diversely distributed and the flights shape should avoid hinder particles entering and exiting it. [7.19], [7.20], [7.21]. For an optimum performance of these blades in a rotary dryer, the volume of material must be less than 15 % of the drum volume, [7.22].

The purpose of this research was to evaluate the leaves and stems separation by the action of a rotary sieve, provided with lifter flights; to find under which conditions of slope, rotary velocity and moisture content of the mixture, the best separation quality is reached, and to determine if this kind of sieve could be used inside a rotary drum dryer with the final aim of reaching a rotary and separation device, taking into account that the sieve must keep the leaves inside while the stems flow through it during the rotation. The best behavior will between most of the leaves remain in the drum.

7.3 THEORY

In accordance with [7.23], the critic velocity of a rotary sieve is the rotation when the centrifugal force equals the material weight. Over it, the centrifugal force reduces the output of material.

At this state

$$r.\omega_c^2 = g \tag{7.1}$$

and then, the critic revolutions are:

$$N_c = \frac{1}{2\pi}\sqrt{\frac{g}{r}} \tag{7.2}$$

The working operation must be between ½ and ¾ of such critic revolutions.

For the test drum of figure 7.1, the critic revolutions are 4.9 s^{-1}, and then its operation must be between 2.5 and 3.7 s^{-1}.

7.4 EXPERIMENTAL PROCEDURE

The sieve test was developed in batch rather than with continuous feeding of material. This way, an instant picture of the behavior of the machine is investigated, which could be integrated in a posterior research in a continuous test.

A rotary drum of 400 mm diameter and 800 mm long, which wall is a sieve with 60% of free area and round holes of 17 mm in diameter, was used. It rotated for the action of an electric motor and belts; the motor rotation speed was changed with a frequency control delivering drum speeds of 1.0, 2.1 and 4.2 s^{-1}. A brush in the external upper part of the drum was provided for its continuous cleaning. The drum slope angle α was kept to 0, and for a batch testing, the feeding and discharge ends were closed to avoid the output of material.

Inside the drum three EHD flight lifters spaced at 120° were used to cascade the material, to reach a more homogenous distribution over the sieve, to give better agitation to the mixture and, as this sieve is part of a rotary drum dryer, also to develop the function of drying. Figure 7.1.

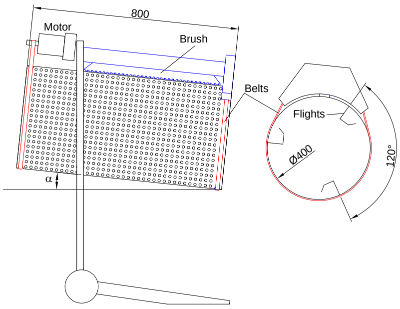

Figure 7.1. Rotary drum sieve.

Three kilogram of material were sliced into pieces of 20 mm and dried at 60° C. The dryer trays were removed after 30, 60, 75, 90 and 105 min in order to obtain a profile of Moisture Content to characterize the separation.

500 g of material from each moisture content were introduced in the rotary sieve. A plastic shed on the ground under the sieve allowed to collect the separated material during rotation. Once the sieve was turned on, the separated material was taken at 5, 10, 15, 20, 25, 30, 35, 40, 45, 60, 75, 90, 120, 150 and 180 s. and weighted; at the end the remaining material on the sieve was also collected.

Subsequently, the separated material and the remaining on the sieve were classified into leaves and stems, grouping the complete or part of a leaf, leaves joined to a piece of stem in the leaf group and in the group of stems the single or composed stems. The weight of these fractions at each separation time was measured. The same test was conducted at the three speed rotations of the drum.

For the test at the speed of 1.0 s^{-1}, a size distribution analysis was conducted. For this purpose, the collected material separated by the rotary sieve was weighted and carefully spread over a white page and photographed. The size measurement was performed using ImageJ software.

A test of advance velocity was performed. Twenty red papers, used as markers, were added and randomly distributed in the sample of 500 g, and then the material was introduced into the upper end of the rotary screen. The tests were developed at all the rotation speeds of the rotary sieve. The slope of the screen for each test was 3°, 4° and 5°, following the procedure of [7.24].

The tests were conducted in a greenhouse and with an empty space at the set sides to avoid air flow interferences. The higher end of the sieve was capped to prevent the return of material and advance completely to the other end, to perform a batch test.

At the front end of the inclined sieve, a video camera was placed recording each test. The videos were analyzed to determine the time instant in which each red marker leaves the sieve. Each run was allowed to proceed until all papers had come out of the screen. For each slope 5 replicates were made.

7.5 RESULTS AND DISCUSSION

All the experiments were performed at each moisture contents appearing in Table 7.1. This moisture contents are the average of the material, because there always are differences between leaves, stems and grass, which values are also shown.

Table 7.1. Average moisture content (χ) of the used material. (g water g^{-1} dry mass)

Drying time (min)	Average	Ryegrass	White Clover	Leaves	Stems
0	3.77	2.29	2.88	3.76	8.11
30	3.19	1.75	2.10	2.60	6.30
60	1.37	0.80	0.85	0.75	3.10
75	1.75	1.00	1.10	1.15	3.90
90	0.90	0.65	0.55	0.40	2.00
105	0.24	0.35	0.30	0.10	0.40

7.5.1 Separation Fraction

In accordance to [7.25], the rate of separation S for leaves S_l, and for Stems S_s is:

$$S_l = \frac{W_{ls}}{W_{st}} \qquad\qquad S_s = \frac{W_{ss}}{W_{st}} \tag{7.3}$$

and the distribution function f_w is

$$f_w = \frac{w}{w_0} \tag{7.4}$$

After 3 minutes of rotation in the fresh state, most of the leaves have been separated from the stems, so this time was used for the comparison of total separation as showed in figure 7.2. The stems are well separated at all moisture contents and at all rotary speed of the drum but the highest rates of separation at all the rotation speeds were in the lowest moisture contents.

At 4.2 s^{-1}, the highest Ss was 96 % at $\chi = 0.24$ and the lower at $\chi = 1.75$ and 3.77 with efficiencies of separation of 74 and 77 % respectively.

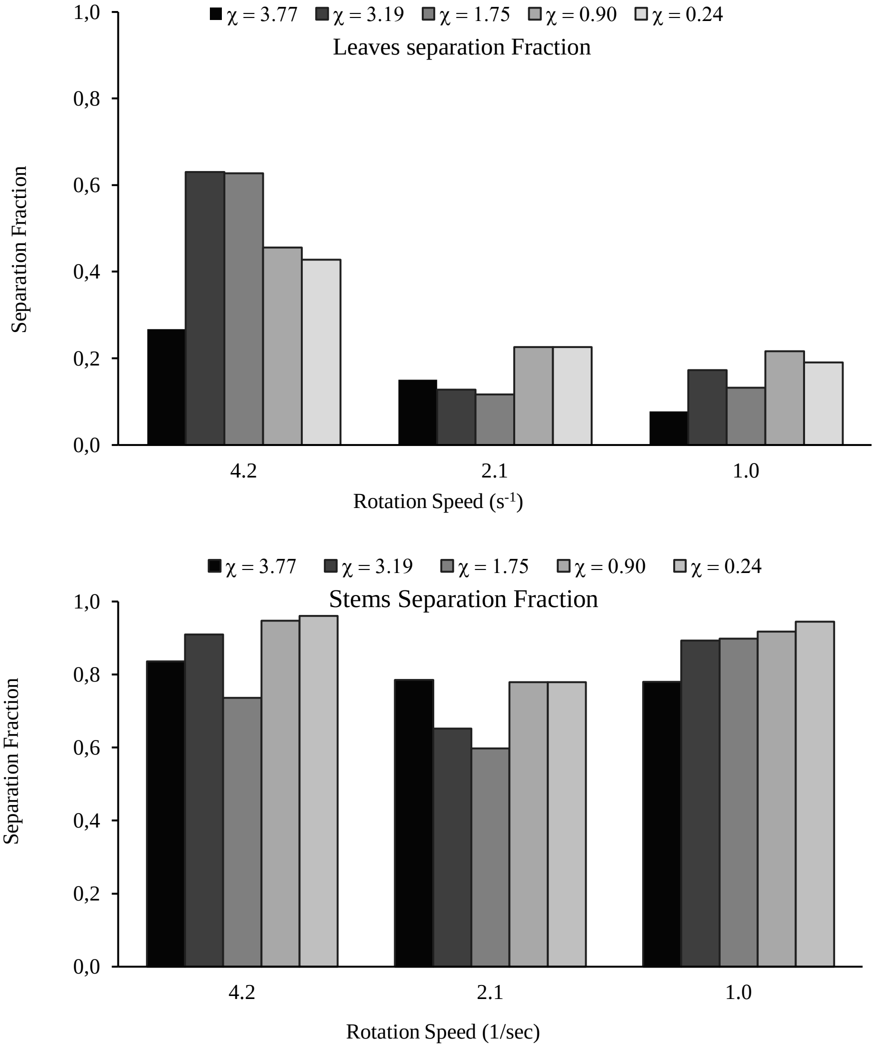

Figure 7.2. Total separation after 3 minutes of rotation.
χ (g water g^{-1} dry mass)

When the velocity was 1.0 s-^{1}, *Ss* was near 90 % for all the Moisture Content except at χ=3.77 when it was 78%. And at 2.1 s^{-1}, *Ss* was around 80 % for all the moisture contents except for χ = 3.19 and 1.75 when it was 65 and 60 % respectively.

The former shows that at lower moisture contents, and all the rotation speeds the material moves easily through the sieve; with drying it lost size and the parts of the mixture could not stick to each other.

The best results were obtained at the lowest rotation speed, at which, after 3 min of movement, 8% and 19% of the leaves had passed through the mesh at χ = 3.77 and χ = 0.24 respectively. These leaves corresponded to small pieces resulting from the cutting process. At a rotation of 4.2 s^{-1} there was low separation of leaves, except for the freshest, which tried to form a roll and broke down as the machine rotated and then they dropped out of the sieve.

7.5.2 Stems separation along the time

Figure 7.3 shows the Stems Separation Function (w/w_0) of eq. 7.4 at several rotary speeds, and moisture contents.

The stems at all moisture content were fastest separated at 4.2 s^{-1} and slowest at 1.0 s^{-1}. Although, with the material at χ = 0.24 there was the same separation function in the first 60 s for speeds of rotation of 2.1 and 1.0 s^{-1}, after which the behavior was similar to the other moisture contents.

At a velocity of 4.2 s^{-1}, which was near to the critic revolutions, the stems separation function was different for every moisture content, but it did not seem to be a trend. Nevertheless, at a speed of 2.1 s^{-1}, which was in the range of optimum work, the separation was faster for the fresh material than for the driest. At 1.0 s^{-1}, under the optimum range, the same amount of material was released at all the moisture contents until 80 s, and then the fresh stems were released faster.

In accordance to [7.23] the rate of releasing of particles of one size, across a sieve is proportional to the number or mass of the particles of such size in the sieve in any time, in the way:

$$\frac{dw}{dt} = -k.w$$

And for one given time:

$$w_2 = w_1.e^{-k.t}$$

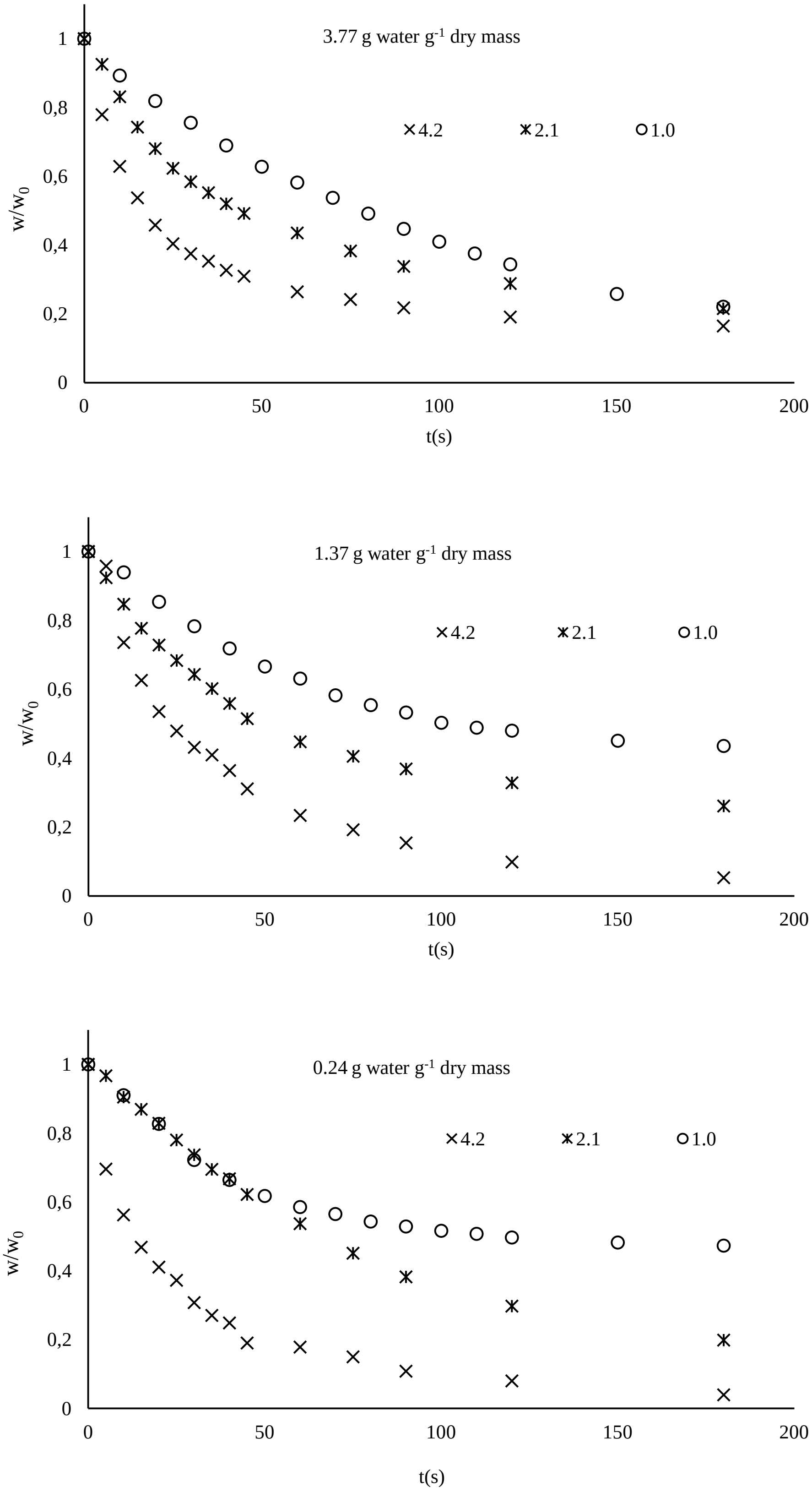

Figure 7.3. Stems separation function w/w_0.
Rotary velocity in rad s^{-1}

However, the relation that better fit the experimental data was:

$$f_w(t) = a.e^{-k.t} + c \tag{7.5}$$

Coefficients of eq. 7.3 are shown in table 7.2.

Table 7.2. Coefficients of the Stems Separation Function.

Rotation Speed s^{-1}	**4.2 s^{-1}**				**2.1 s^{-1}**				**1.0 s^{-1}**			
χ g water g^{-1}dry mass	**k**	**a**	**c**	**R^2**	**k**	**a**	**c**	**R^2**	**k**	**a**	**C**	**R^2**
3.77	0.053	0.758	0.212	0.990	0.025	0.750	0.243	0.994	0.009	0.959	0.018	0.999
1.37	0.041	0.669	0.312	0.993	0.023	0.733	0.265	0.998	0.018	0.644	0.406	0.999
0.24	0.049	0.833	0.100	0.979	0.012	0.936	0.082	0.999	0.027	0.578	0.475	0.998

7.5.3 Leaves passing the sieve

There was a given amount of leaves exiting the sieve as this rotates. To visualize this amount, the rate of weight of leaves to the total weight of the material leaving the screen at each time interval was plotted against time. Figure 7.4 shows this rate.

The amount of leaves in the sieved material was less when the sieve rotated at 2.1 s^{-1} than in the other two speeds, while at 4.2 s^{-1} this ratio was the higher. At speeds of 1.0 and 2.1 s^{-1} leaf output was high at the rotation start; this corresponded to fragments of leaves as cutting result. Then this amount reaches a minimum, between 5% and 10%, at 60 and 70 s for the material at 3.77 and 1.37 g water g^{-1} dry mass respectively and rotation of 1.0 s^{-1}; whereas if the rotation is 2.1 s^{-1}, the minimum is between 10% at 20 s for the fresh material and 3.6% at 35 s for the dry material. Then the number of separated leaves increases linearly, corresponding to complete and deformed leaves due to the rotation drops out of the screen.

At a rotation of 4.2 s^{-1}, the output of leaves increases linearly during the first 30 s. instead of decreasing, after which it continued to increase linearly but at a slower pace.

In general the presence of leaves in the removed material is greater for the dry material than for the fresh material, which may be due to reduced particle size with drying.

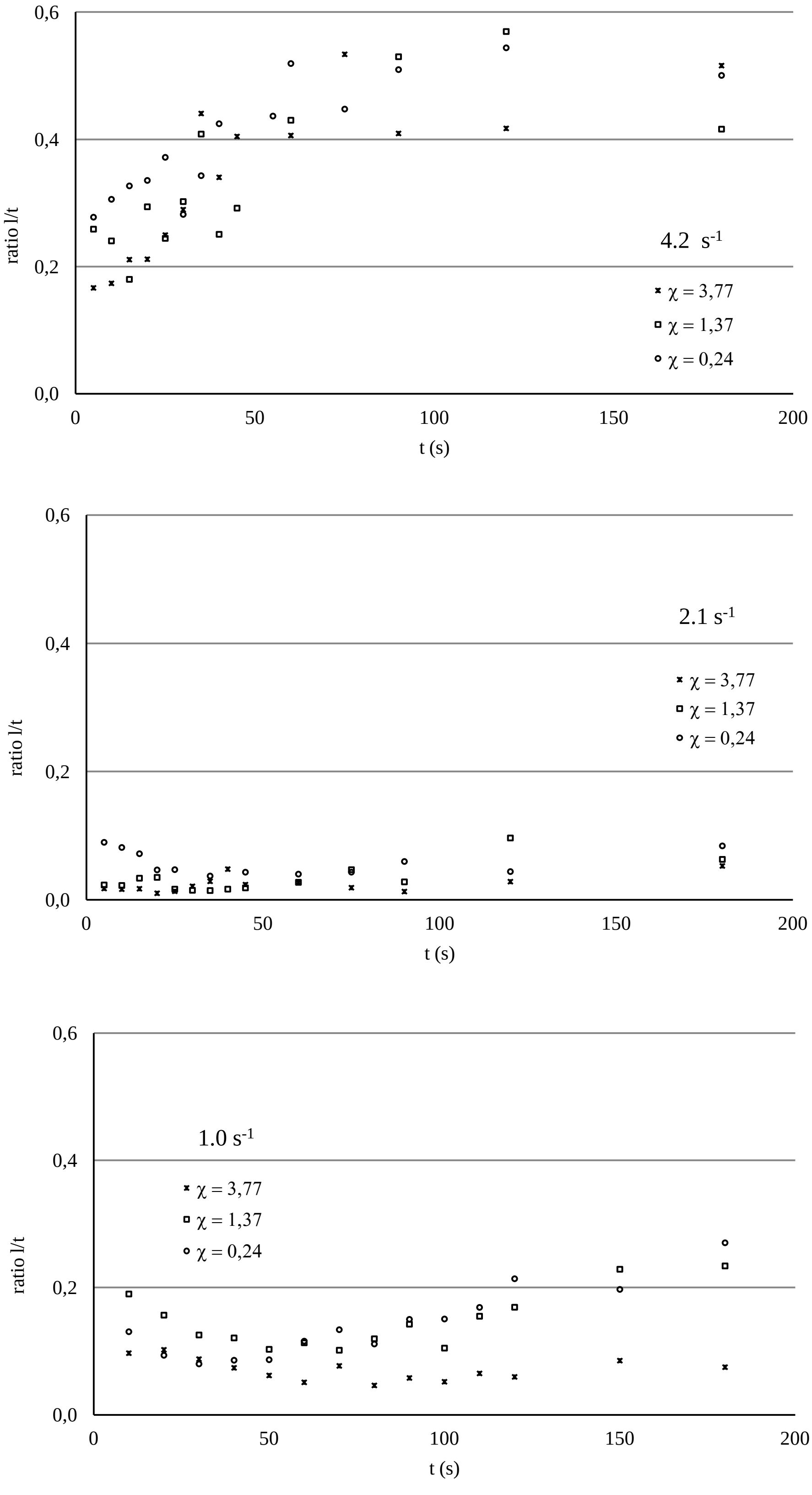

Figure 7.4. Ratio of mass of leaves to total mass along the time.
χ (g water g^{-1} dry mass)

7.5.4 Particle Size Distribution Analysis

The analysis of particle size distribution seeks to establish the separate particles variation throughout the screening process. This analysis was done for 1.0 s^{-1}. The graphs of the distribution are close to those of the Weibull probability density function:

$$f(x) = \frac{\beta(x-\delta)^{\beta-1}}{\theta^{\beta}} e^{\left[-\left(\frac{x-\delta}{\theta}\right)\right]} \qquad x \geq \delta$$

And cumulative distributions function:

$$F(x) = 1 - e^{\left[-\left(\frac{x-\delta}{\theta}\right)\right]}$$

The parameters for the particle size distribution of the material at χ of 3.77, 1.37 and 0.24 g water g^{-1} dry mass; are shown in Table 7.3.

Table 7.3. Weibull Parameters for the particle size of the mixture of grass

χ g water g^{-1} dry mass	β	θ	δ	R^2
3.77	0.982	264.7	30.850	0.985
1.37	1.048	258.599	29.872	0.993
0.24	1.540	65.309	29.506	0.981

During the screening process, these parameters are changing due to the separation between stems and leaves. Figure 7.5 shows the graphs of particle size distribution for various moisture contents at 10, 50, 100 and 180 s of sieving.

With fresh material there is not a trend related to the time of screening. For 1.37 and 0.24 g water g^{-1} dry mass there is a clear difference between the times of separation, this way for the first seconds there is a presence of uniform particle size, whereas for the last moments there are more particles sizes. This shows that during the first moments of sieving more stems are released, while towards the end the output of the leaves occurs, as already discussed in Figure 7.2.

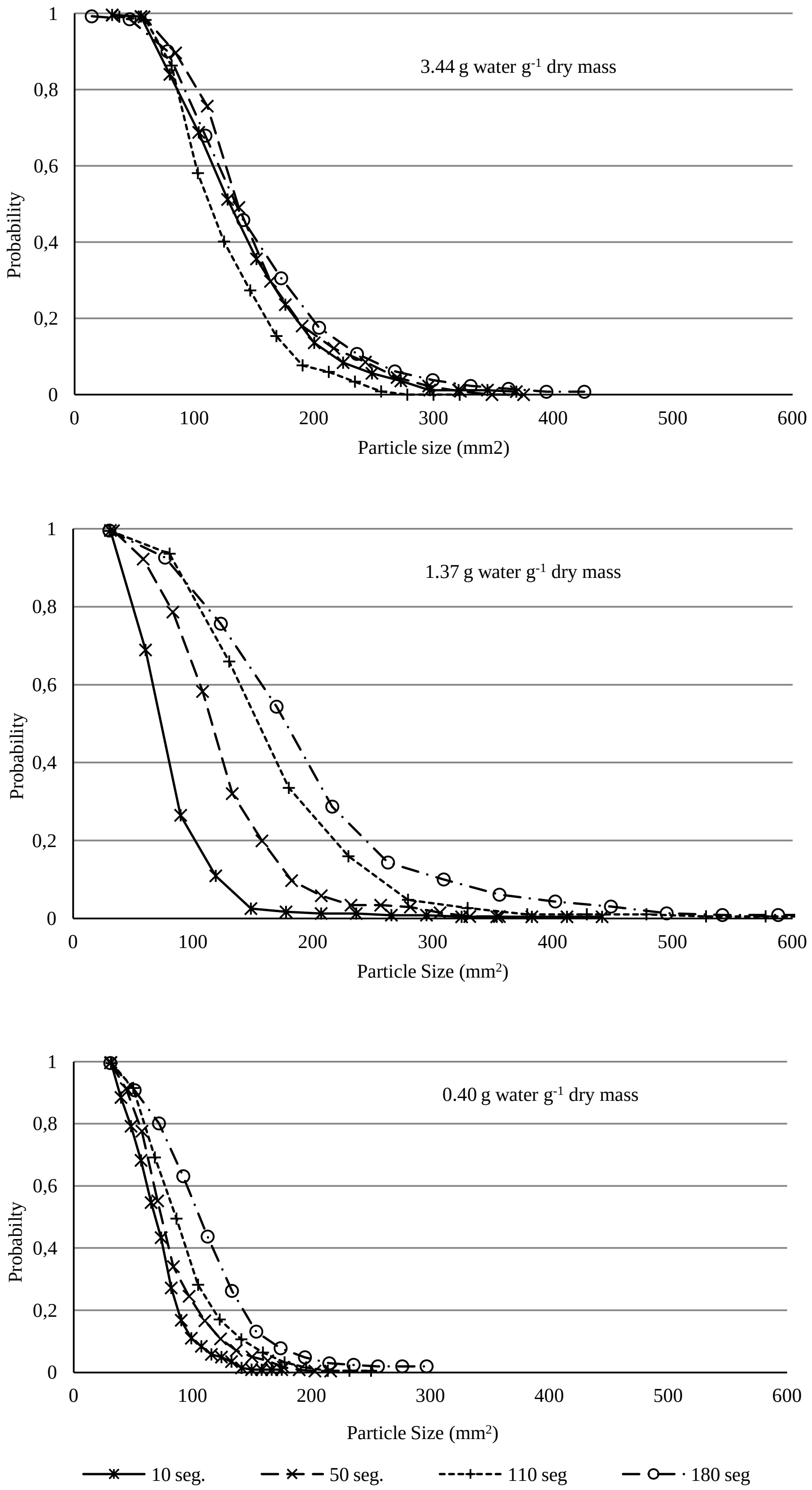

Figure 7.5. Cumulative distribution of particle sizes for various separation times.

Figure 7.6 shows the change of the parameters θ, δ and β for each measurement time.

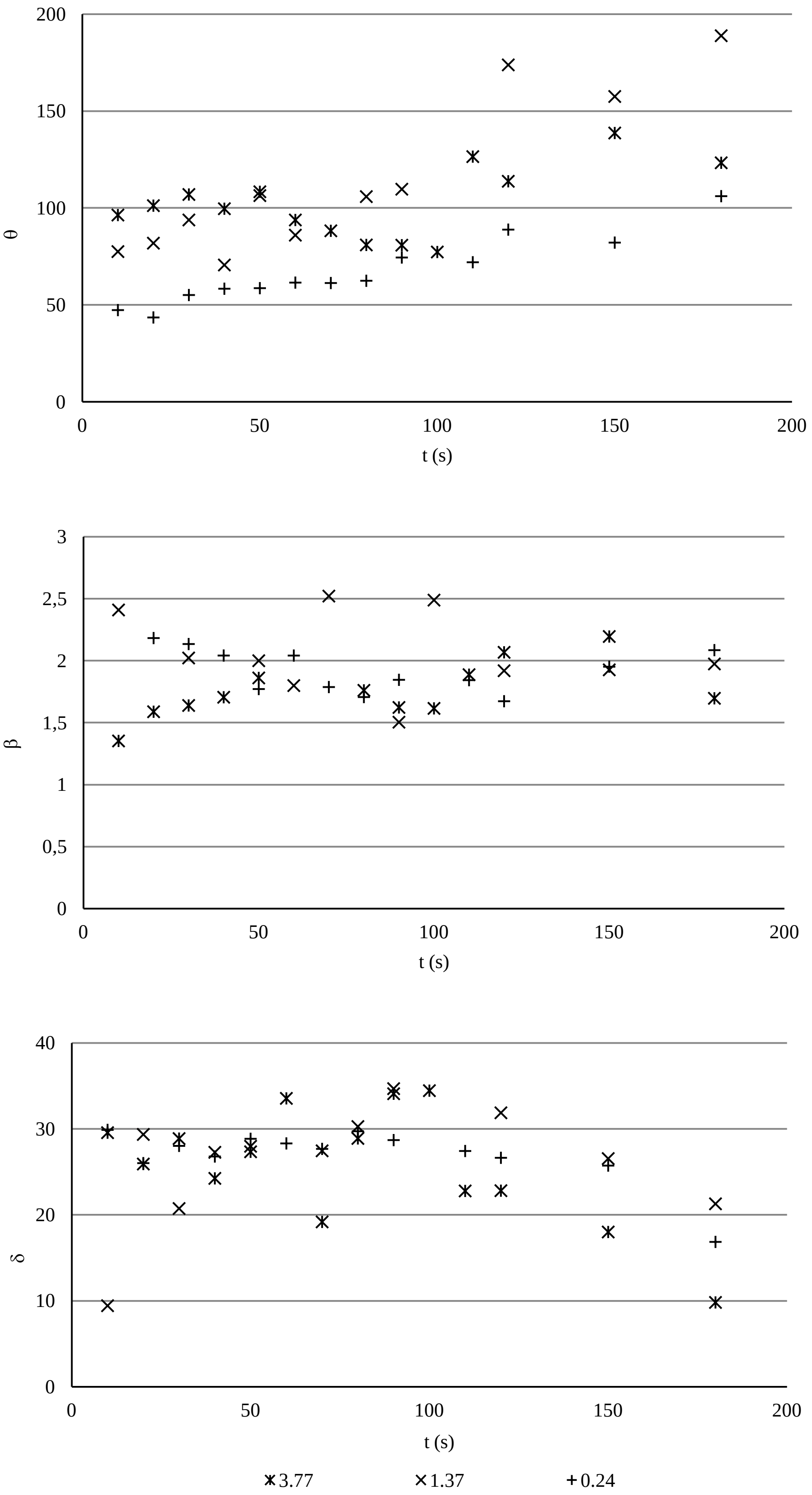

Figure 7.6. Variation of the Weibull parameters along the sieving.
χ (g waterg^{-1} dry mass).

Throughout the screening θ has a nearly linear variation, especially with a moisture content of less than 1.34 g water g^{-1} dry mass. When the material is fresh, this parameter is increased with the time of screening, but the trend is no clearly linear. Furthermore the β shape parameter has an average value of 1.87 and a standard deviation of 0.28 throughout the process and for all moisture contents. No wonder, that the parameter δ has a nearly constant value for all moisture content and separation times with mean of 26.24 and standard deviation of 5.78 corresponding to the minimum particle size present in all measurements.

7.5.5 Advance Velocity

In accordance with [7.17], the time characterizing the movement is that when half of the markers have left the lower end of the drum. As the length of the drum is 800 mm, the advance velocity was calculated. Figure 7.7 shows the tendency of the advance velocity at several slopes of the drum and rotation speeds.

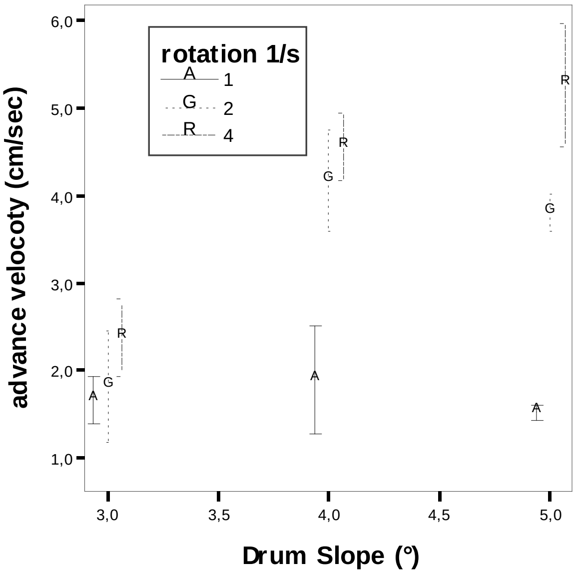

Figure 7.7. Advance velocity of the particles as function of drum sieve slope and rotation speed.

For rotation speeds over 2 s^{-1} the advance velocity of the particles raises as the drum slope increases. But at the slowest rotation, there seems to be not much influence of the slope. In the same way at the highest rotation speeds, raises the advance velocity, appearing the greater speed differences at the higher slopes of the sieve.

These values of advance velocity are useful for the calculation of the sieve length. It must be taken into account that with high slope of drum, the necessary length of it is bigger; in order to get enough stems separation.

7.6 CONCLUSIONS

It has come a characterization of sieving a mixture of stems and leaves of clover and ryegrass to various moisture contents, using a rotating sieve with lifter flights.

There was stem separation efficiency between 74 and 96% for material moisture contents of 1.75 and 0.24 g water g^{-1} dry mass respectively and rotational speeds of 4.2 s^{-1}.

At the lower moisture contents, stems separation of the mixture is better than when the material is fresh, for all rotational speeds.

The best performance of the separation occurs at a speed of 2.1 s^{-1}, which is in the operating range according to the critic revolutions of rotation.

Although there was always presence of leaves in the screening, these were lower with fresh material and a turning velocity within the optimum range.

It is possible to get a separation between leaves and stems and reach a high efficiency of classification using a rotary sieve.

These observations allow concluding that a rotary sieve can be used inside a rotary drum dryer of hay, in order to make the drying and the separation between leaves and stems in the same device. This can be allocated along the first drum for leaves, because the results show a good performance for all the material moisture content. This leads to a separate drying of the main components, resulting in better quality of the product and saving of energy.

7.7 SYMBOLS LIST

f_w:	Distribution function. w/w_0
g:	Gravity acceleration (9.81 m s^{-2})
N_c:	Critic revolutions of the drum (rad s^{-1})
r:	Drum ratio (mm)
S_l:	Separation rate of leaves
S_s:	Separation rate of stems
w:	Weight of particles of a given size over the sieve in a time t (g)
w_0:	Original mass of particles of a given size over the sieve (g)
W_{ls}:	Weight of the separated leaves (g)
W_{lt}:	Weight of the total initial leaves (g)
W_{ss}:	Weight of the separated stems (g)
W_{st}:	Weight of the total initial stems (g)
W_l:	Weight of leaves (g)
W_t:	Total weight (g)
a, k, c:	Constants in equation 5
α:	Slope angle of the drum
χ:	Moisture content (g waterg^{-1} dry mass)
ω_c:	Angular velocity (rad s^{-1})
β :	Shape parameter which indicates the distribution profile curve, $\beta > 0$
θ :	Scale parameter, indicates how sharp or flat the distribution graph is, $\theta > 0$
δ :	Location parameter, indicates the beginning of the distribution, $\infty < \delta < \infty$.
x:	Variable in the Weibull distribution

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8 DESIGN OF A CONCENTRIC CYLINDER ROTARY DRYER FOR DRYING AND SEPARATION OF LEAVES AND STEMS OF HAY

8.1 ABSTRACT

The drying and separation of leaves and stems of a mixture of With Clover and Ryegrass into a rotary dryer, leads to prove a rotary dry prototype. This is composed by three rotating concentric cylinders and a cylindrical sieve in the more internal drum. As the leaves shall remain in the internal drum while the stems shall cross the sieve and advance through the middle and external drum, the velocity of the air must be less than that require dragging the material, i.e. 1.6 m/s for leaf and 4.5 for stems. The best disposition of the prototype was when the air entrance was made in front of the middle cylinder and when the entire length of the internal drum was a sieve. Lifting flights are used in all the drums, including the sieve.

8.2 INTRODUCTION

Rotary dryers are widely used for different types of materials, such as chemicals and pharmaceuticals, foods, industrial waste and fertilizers [8.1]. Among agricultural materials for these dryers: alfalfa [8.1], chilies [8.3], coffee [8.4], grains [8.5] forestry biomass [8.6] vegetables [8.7] and others are reported.

This type of dryers are used in industries for the production of pellets and cubes of forage plants such as alfalfa, timothy and bromegrass; in Europe and North America due to the homogeneity of the final product. [8.9].

In this type of composite material, leaves are dried at a different rate than the stems, so an over- and under-drying of the different components occurs. That can be prevented by separation during drying. Also with regard to their use, these parts have different protein composition as in the case of alfalfa. [8.10]

In many dryer plants in Europe and North America, direct contact type rotary drum dryers are used for forages, which produce uniform quality product because of its relative long residence time and good mixing of the product. In these driers the energy consumption is between 3 and 8 MJ kg^{-1} dry product. If the dryer is badly designed or operated, it could lead to failures in the quality and to more energy consumption. [8.9].

A rotary dryer consists of a cylindrical plate rotating about its longitudinal axis. It is slightly sloped to the horizontal, inducing solids to flow to the end direction [8.27]. Lifting flights cascade the material that is continuously introduced into one end of the dryer. The drying occurs by the contact of the hot air with the material in the Cascades. [8.2]. As a result of the long residence time and mixing, a material with near a uniform moisture content is obtained. The heated air enters and flows counter or concurrently to the flow of the drying material.

In the dryer, the transport of the wet material, the heat exchange between the hot air and the material and the transfer of vapor from the material to hot air occur simultaneously. At every drop of material, this advances along the drum by the action of air, the angle of the flights and the drum. [8.8].

There are reports of adaptations of this type of rotary dryers for separation of leaves and stems especially of lucerne. A small dryer of three concentric cylinders was adapted as shown in Figure 8.1. [8.10].

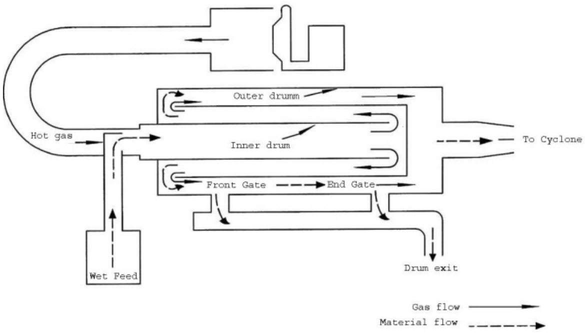


Figure 8.1. Three-pass rotary drum.
Source [8.10]

In this dryer, the two inner cylinders rotate while the outer is fixed; in this, two gates allow the output of heavier material (stems), and using the drag aerodynamic properties, the leaves drop the cyclone at the back. The study reports that with material entering with 72 g water g^{-1} dry mass, there is an average difference of moisture content at the outlet of 9.3 and 1.5 g water g^{-1} dry mass for stems and leaves respectively. Moreover, an efficiency of leaf separation between 62 and 89% was reported and a purity of leaves at the outlet of the cyclone between 65 and 78%.

A three concentric cylinders dryer, was developed for forest products, municipal and industrial wastes and recycling of animal protein. In this, an adaptation of the initial chamber was made, thus achieving four drying zones. [8.11] Figure 8.2.

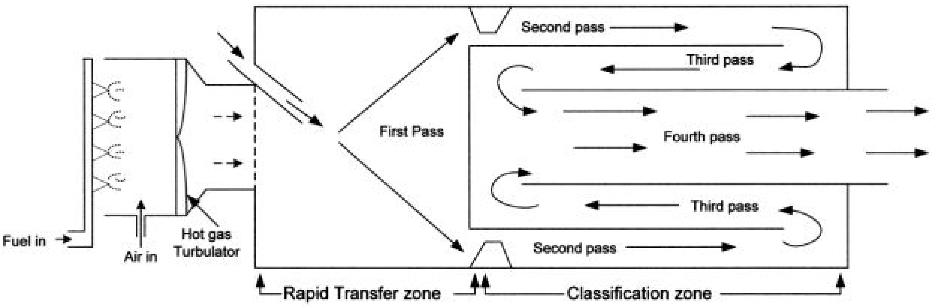


Figure 8.2. Quadpass.
Source [8.11]

Since there is turbulence of air in the initial area, the developers ensure that it gives a better aeration of the product with high moisture content and then a better dry uniformity, because most of the moisture evaporation occurs in this area. In zones two to four the air runs faster because of the reduction of the cross section and tends to separate the lighter material, such as leaves, which leaves the dryer faster, while finer particles remain longer.

In the proposal of the current research, a modification allows the leaves and stems advancing with the rotation. There is an initial zone of feeding of material, with high air turbulence but with the incorporation of a circular sieve, which makes an initial separation of the components of the mixture.

This way, the design wants improve the separation of the components of the mixture during the drying and give to each of them the condition of air velocity and residence time to reach the desired final moisture content.

A study of the air flow inside the dryers allows appreciate the advantages of the design. For example [8.12] reports a model of a pass quad dryer using Computational Flow Dynamics (CFD) using the standard $\kappa - \varepsilon$ model; where, varying the air inlet area, the assessment of the air flow in the separation zone was made.

Computational Fluid Dynamics has become a very important tool for decision making on design and evaluation of many types of dryers, such as conveyor dryers [8.13], drums [8.14], fluidized beds [8.15], pneumatics [8.16], rotary dryers [8.17], cabinet s for fruits [8.18], [8.19] and rotary kilns [8.20] among many others. Its importance lies in the possibility of making rapid assessments of changes in designs, without incurring in large costs and time. It also allows evaluating the operating conditions in mechanisms in which it is not easy to make direct observations.

The main objective of this research was to determine the conditions of air flow inside the concentric drums rotary dryer, allowing the development of a differential drying of agricultural material composed by stems and leaves.

8.3 MATERIALS AND METHODS

A rotary dryer with three concentric cylinders for mixtures of agricultural materials composed by leaves and stems, such as Lucerne or Ryegrass and Clover was designed. Given that there is a difference in drying time between the stems and leaves of the mixture, a cylindrical sieve drum at the beginning of the Internal Cylinder (IC) was implemented, so that the stems pass to the Middle Cylinder (MC) and follow to the External Cylinder (EC) in a large path, while the leaves remain in IC during a shorter time, as is shown in Figure 8.3.

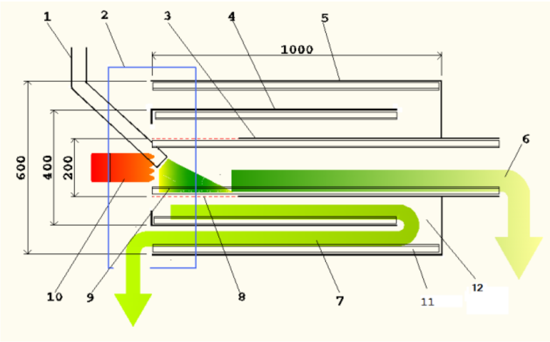


Figure 8.3. Dryer diagram.
1. Material Input, 2. Cover, 3. Internal Cylinder (IC) for leaves, 4 Medium Cylinder (MC), 5. External Cylinder (EC), 6. Leaves, 7. Stems, 8. Sieve, 9. Mixture, 10. Hot Air. 11. Flights. Measurements in mm.

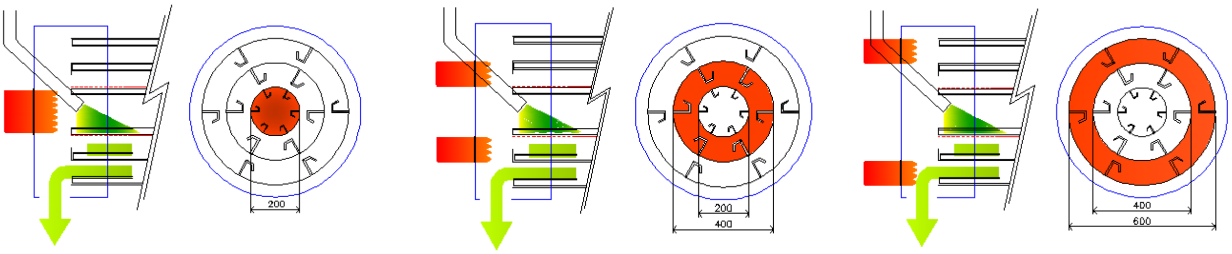
According to the results reported in [8.21], during drying the separation between leaves and stems in a rotary sieve can be done at any moisture content. Using a sieve of 400 mm in diameter and 60% of porosity, with a rotational speed of 1.0 s^{-1}, after three minutes of rotation a stems separation quality from 78 to 90% was achieved. With fresh material, at rotational speeds of 1.0, 2.1 and 4.2 s^{-1}, 80% of the stems have been separated after 200, 190 and 110 s, respectively. With an inclination of 3°, the forward speed of the material in a rotary drum was 1.7, 1.8 and 2.4 cm s^{-1}, for rotational speeds of 1.0, 2.1 and 4.2 s^{-1} respectively. With these results the calculated sieve lengths shall be between 2.6 and 3.4 m, to reach the complete separation.

According to the terminal velocity of this material at different moisture contents, the air velocity should be less than 1.6 m s^{-1} in the IC and less than 4 m s^{-1} in MC and EC, in order to prevent the entrainment of the leaves and stalks. These shall move because the geometry and inclination of the flights. [8.2].

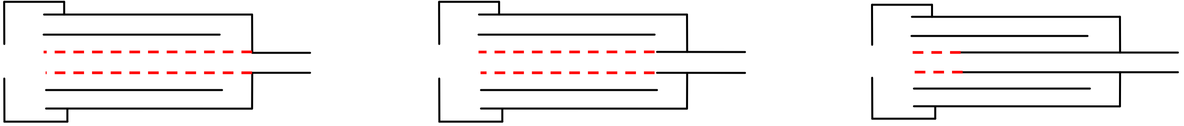
According to [8.24] the amount of material in the dryer most correspond to 15% of the total volume. The geometry of the flights was an Equal Horizontal Distribution [8.3] which gives an equal distribution of the showered material on the horizontal diameter of the drum [8.25], [8.26], [8.27] and ensures excellent gas-solid contact [8.28]. It was calculated using the fresh material density and considering that the volume of material in these must be 15% of the dryer volume. [8.4].

To visualize the air movement in the dryer a Computational Fluid Dynamics -CFD modeling was done. For this, the dryer was drawn in 3D in AutoCad, subsequently it was meshed in Gambit 2.230, using a hex-barrel configuration for most elements and hex-core for some complex shapes. The model was run in Fluent 6.3.26.

Model runs were made in order to achieve an air velocity less than or equal to 1.6 m s^{-1} in the IC, and to verify the distribution of velocities along the dryer. The air had a temperature of 80°C, with density of 0.6712 kg m^{-3} and a viscosity of 2.082×10^{-5} Pa-s.



1. Front to inner cylinder. (ICI) 2. Front to middle cylinder. (MCI) 3. Front to external cylinder. (ECI)



1. Full sieve. (FS) 2. No return zone sieve. (NRS) 3. Entrance sieve. (ES)

Figure 8.4. Variation of the air inlet to the rotary dryer.

In order to find conditions for a better air flow in the three cylinders, three air inlets were evaluated on the cover as in Figure 8.4: 1. Front to the Inner Cylinder Inlet (ICI), 2. Front to the Middle Cylinder Inlet (MCI), 3. Front to the External Cylinder Inlet (ECI). Additionally the length of the sieve was varied as follows: 1 Full Sieve (FS), the mesh goes throughout the IC, up to the end of the middle and external cylinder; 2. No sieve in the return zone (NRS). The same as case 1, but without mesh in the zone parallel to the return between the middle and the external cylinder; 3. A sieve of thirty centimeters length at the beginning of the internal cylinder (ES). In all cases the flights run along the entire inner cylinder even in sieve area. Figure 8.4.

The model uses a distribution of grass inside the dryer at one instant of one turn, as shown in Figure 8.3. For the shape of the cross sectional area of the grass, the angle of friction of the grass (29°) was taken into account [8.5].

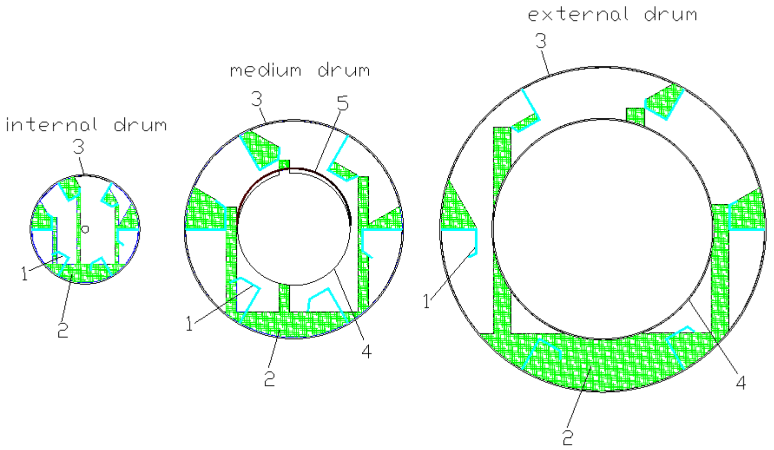


Figure 8.5. Distribution of grass along the drums.

1 Flights. 2. Grass (leaves in the internal cylinder, stems in the cylinders mittel and external); 3 Outer wall of the drum; 4 Inner Wall of the drum; 5. Barrier over the sieve to prevent return of stems.

The density of grass corresponds to the density of the loose material, obtained by measuring the weight of the grass placed without pressure on a vessel of known volume. This was used for both the grass deposited in the flights, at the bottom of the drum and in the cascades from the flights. The density, porosity, viscous and inertial resistance coefficient of each component are shown in Table 8.1.

Table 8.1. Physical properties of the components of the mixture and the sieve.

Component	ρ_r g cm^{-3}	ρ_{bulk} g cm^{-3}	Porosity	Permeability	Viscous resistance	Intertial Coefficient
Ryegrass White clover	0.775	0.074	0.905	0.00048	2080.99	15.15
White Clover leaves	0.669	0.083	0.876	0.00026	3868.55	21.68
White Clover Stems	0.643	0.122	0.810	4.596x10^{-7}	2175711.07	577.94
Sieve	-	-	0.700	-	0	768

8.4 BASIC GOVERNING EQUATIONS OF MODELLING THE DRYER.

From the basic laws of conservation of mass, momentum and energy; equations of continuity, Navier Stokes and energy are derived respectively. [8.23]

The Continuity is expressed by:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \bar{v}) = S_m$$

Where S_m is the mass added to the continuous phase due to any source.

The Conservation of momentum in an inertial reference frame is:

$$\frac{\partial \rho}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F}$$

Where ρ is the static pressure, $\bar{\bar{\tau}}$ is the stress tensor, and g and $\vec{F}$ are the gravitational body force and external body forces, respectively. The stress tensor $\bar{\bar{\tau}}$ is given by

$$\bar{\bar{\tau}} = \left[(\nabla \vec{v} + \nabla \vec{\mathrm{v}}^{\mathrm{T}}) - \frac{2}{3}\nabla.\overrightarrow{vI}\right]$$

Air velocities, required to move the leaves and stems of ryegrass and white clover, get a turbulent regime, according to the results of Lozano and Hensel [8.22]. According to [8.19] the standard k-ε model is successfully used in industrial applications. In this semi-empirical model there are equations describing turbulent kinetic energy transport (κ) and its dissipation rate (ε). The transport equations to obtain them are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b + \rho\varepsilon - Y_M + S_k \tag{8.1}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{8.2}$$

G_k is the generation of turbulence kinetic energy due to mean velocity gradients, and G_b is due to buoyancy. Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. C_{1s}, C_{2s}, and C_{3s} are constants. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively. S_k and S_ε are user defined source terms.

The viscosity, μ_t, is:

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon}$$

C_μ is a constant.

The values used by default in the present model are:

$C_{1\varepsilon}$= 1.44, $C_{2\varepsilon}$= 1.92, C_μ = 0.09, S_k = 1.0, S_ε = 1.3.

G_k, the production of turbulent kinetic energy is.

Consistent with the Boussinesq Hypotesis

$$G_k = \mu_t S^2$$

S is the main module of the rate-of-strain tensor,

$$S \equiv \sqrt{2S_{ij}S_{ij}}$$

The porous media model incorporates an empirically determined flow resistance in the porous region, this model add a momentum sink in the governing momentum equations.

For homogeneous porous media, a viscous loss term and an inertial loss term is added to the fluid flow equation as:

$$S_i = \left(\frac{\mu}{\alpha} v_i + C_2 \frac{1}{2} \rho v_{mag} v_i\right) \tag{8.3}$$

S_i: Momentum sink.

μ: viscosity of the air

α: Permeability, 1/α = viscous loss term

C_2: Internal resistance factor.

For a perforated plate, as the used sieve, the permeability term is neglected.

The value of the loss terms in eq. 8.3 are derived using the Ergun equation 8.4, for a packed bed.

$$\frac{|\Delta P|}{L} = \frac{150\mu}{D_p^2} \frac{(1-\epsilon)^2}{\epsilon^3} v_\infty + \frac{1.75\rho}{D_p} \frac{(1-\epsilon)}{\epsilon^3} v_\infty^2 \tag{8.4}$$

For laminar flow the second term on the right side is neglected and the permeability and inertial loss terms are:

$$\alpha = \frac{D_p^2}{150} \frac{\epsilon^3}{(1-\epsilon)^2}$$

$$C_2 = \frac{3.5}{D_p} \frac{(1-\epsilon)}{\epsilon^3} \tag{8.5}$$

Where

Dp: Is the mean particle diameter,

L: bed dept,

ε: void fraction. Volume of voids divided by the volume of the porous region.

The viscous and inertial loss terms, as well as the porosity of the mixture components and the sieve are summarized in table 8.1.

8.5 RESULTS AND DISCUSSION

In order to analyze the air flow in the dryer, the behavior was observed in three surfaces. The first of them corresponds to a vertical plane dividing the dryer into two halves in the direction of the air flow, this section passing through areas with and without grass. Due to the difference in the air flow in the upper and the lower halves because of the air outlet present in the bottom of the cover, two surfaces were used passing mostly through areas without grass; one surface crosses the axis of the dryer at 45 degrees in the upper part, and another at 45 degrees toward the bottom.

The air velocity profiles were observed along lines on the inclined planes, on areas with just air or grass, as shown in Figure 8.6.

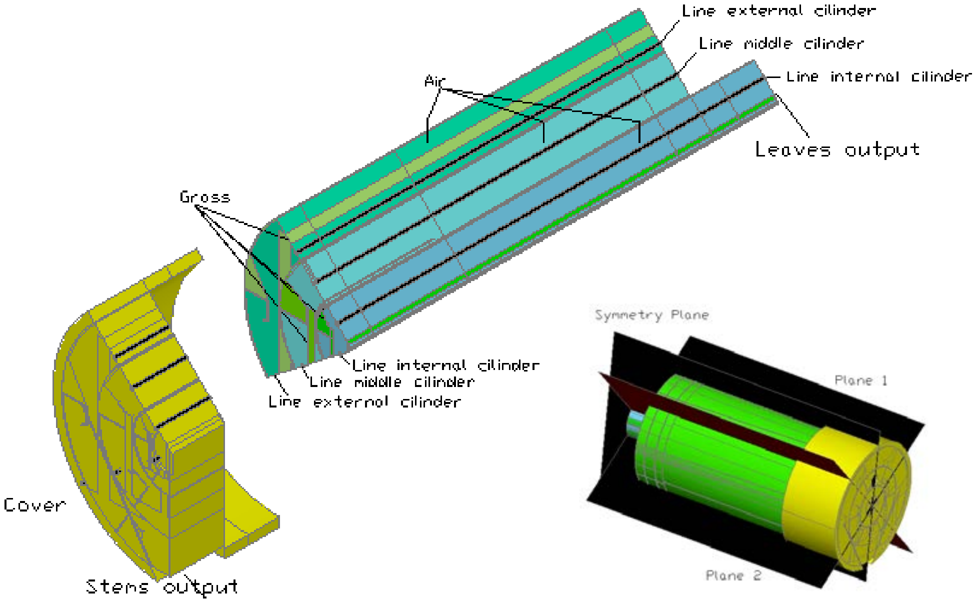


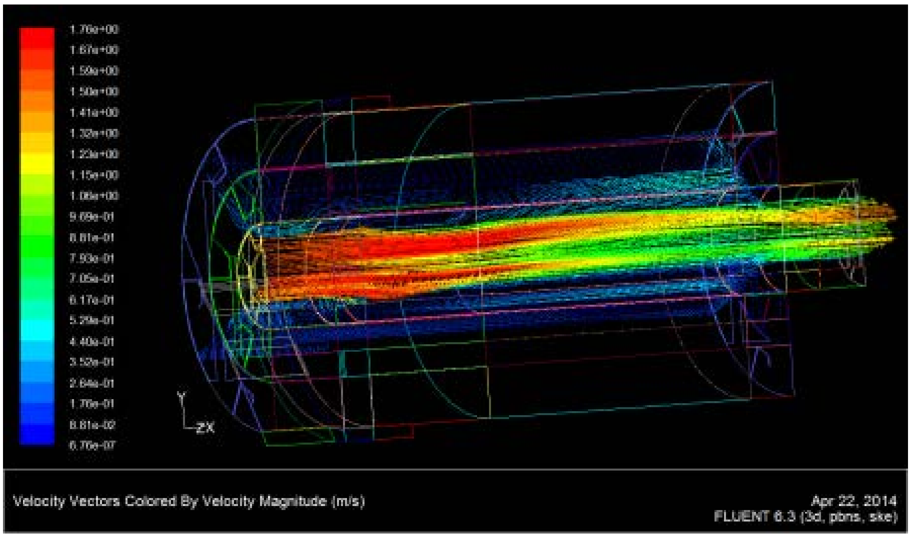
Figure 8.6. Planes and lines for air flow analysis.

Changing the place through which the air enters to the dryer in the cover, its proper distribution in the three concentric cylinders was assessed, keeping the air velocity less than or equal to the drag speed of the grass mixture components.

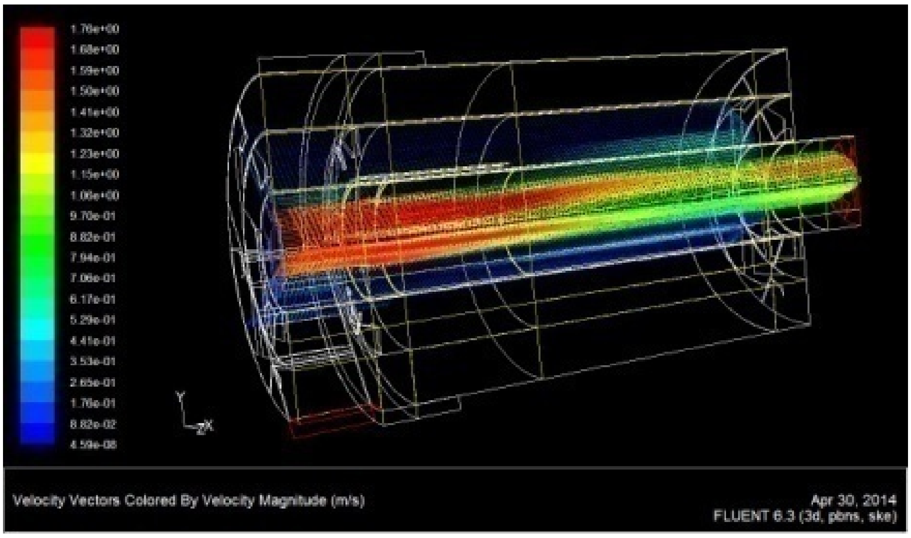
8.5.1 Air in Front of the Internal Cylinder Intake - ICI.

In the ICI case, much of the air followed the IC and that which ran through the sieve lost its speed; while in the IC the speed varied between 1.2 and 1.6 m s^{-1}, in the middle and outer cylinders this varied between 0.2 and 0.5 m s^{-1}.

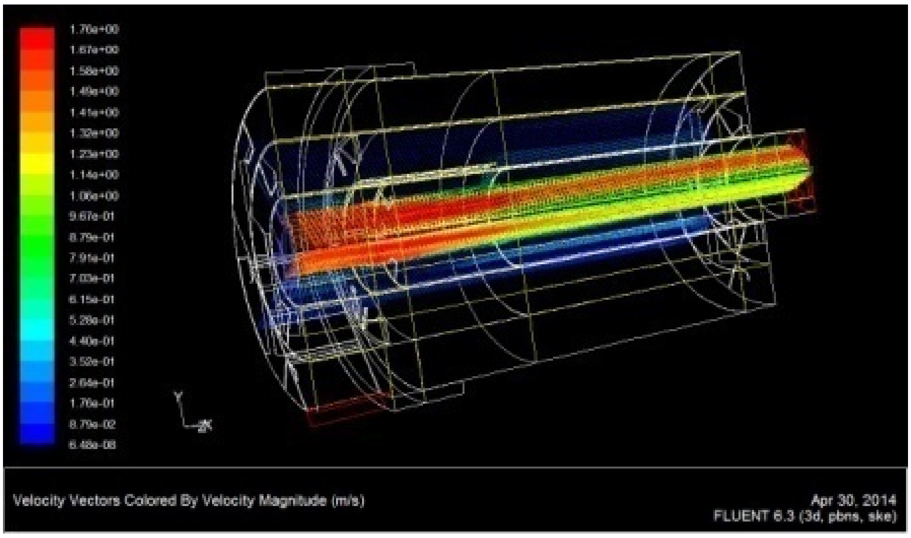
The best air distribution was obtained in the NRS case as is shown in figure 8.7. The velocities in the middle and external cylinders were about 0.6 m s^{-1}, while in the internal cylinder air entered at 1.4 m s^{-1}, and stabilized at 0.6 m s^{-1}.



FS case



NRS case



ES case

Figure 8.7. Air input front the inner cylinder.

The flow distribution in percentage of the air intake is shown in figure 8.8.

In accordance to the allowed cases of length of the sieve, the dyer was divided into 6 zones as shown in figure 8.8. The rows correspond to every cylinder: EC, MC and IC; S is the Sieve. Columns correspond to zones of the dryer divided according to their location with respect to the divisions in the IC: C. Cover; 1. Zone parallel to the Initial part in IC, where the material enters; 2. Zone parallel to the initial 30 cm of sieve; 3. Zone parallel between 2 and the return zone; R. Zone parallel to the return zone; O. output of leaves and air at the end of IC.

Positive numbers are for flow in the direction to the rear output, and negative in direction to the cover.

-48.73	C output											
	CE	-22.72	DE1	-22.72	DE2	-22.72	DE3	-22.72	DER			
	CM	-25.27	DM1	-10.14	DM2	12.62	DM3	38.20	DMR			
	S		S1		S2		S3		SR			
			15.83		22.77		25.58		-15.49			
100	CS	99.99	DI1	84.13	DI2	61.36	DI3	35.78	DIR	51.27	DIO	51.27

Figure 8.8. Mass Flow of air as percentage of the air intake. ICI and FS case.

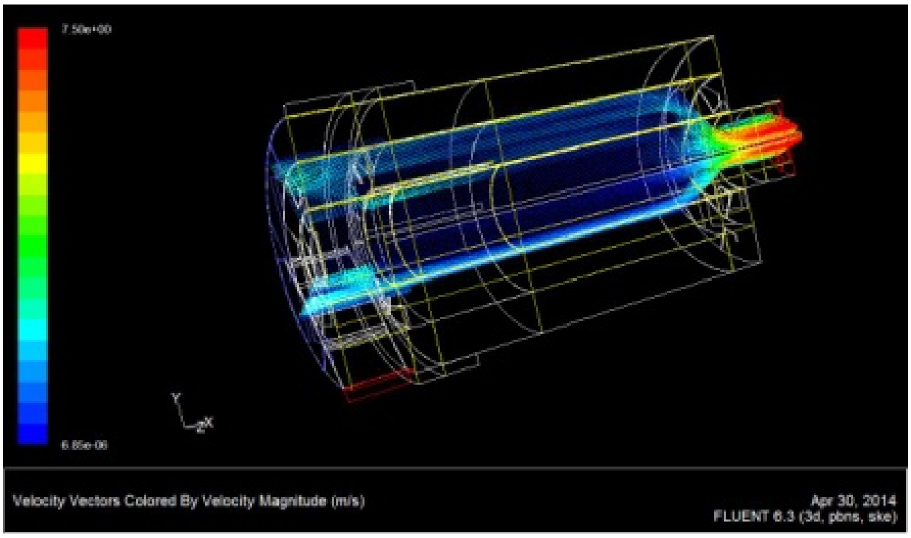
In this case, almost all the air flowed directly to the IC, part was deviated thought the sieve to the MC and just 35.78% reached the return zone. In the middle part of MC, the air flux was deviated to the cover, 25.27 % of the air moved in this direction while in the opposite direction 38.2% reached the return area. 15.49% flowed from here to IC through the sieve. In this way the 51.27 % of the air leaved the dryer in the rear output and it was air that had dried the leaves in the internal cylinder and from air that dried the stems in the second half of the middle cylinder. 48.73 % of air leaved the dryer in the Cover output, this came from the external and middle cylinders after dry the stems.

The main problem of this set was that the air in IC could press the leaves against the sieve, blocking the flow of stems and air.

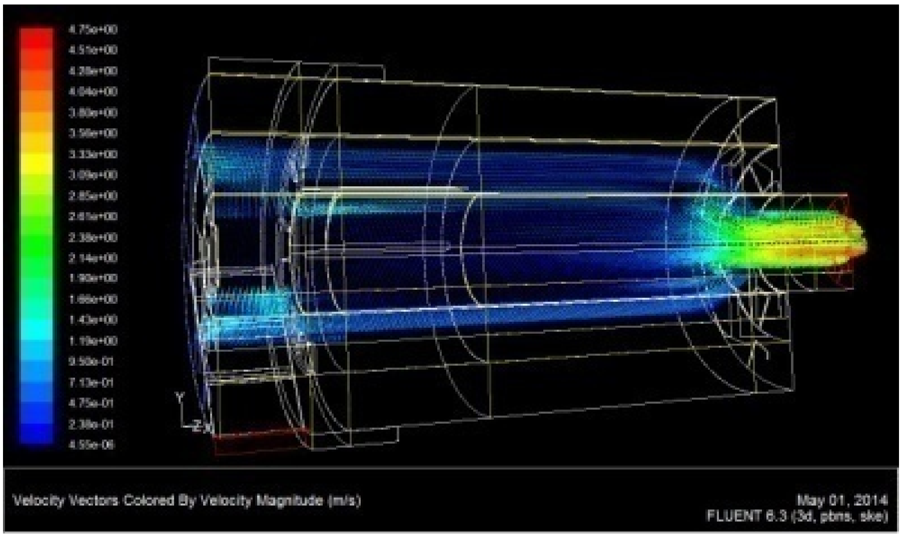
8.5.2 Air in front of the External Cylinder Intake. ECI

When air entered in front to External Cylinder, this was divided into a stream flowing to MC and other to EC. Along MC small amounts of air entered through the sieve into IC, however this amount was bigger towards the end in the return.

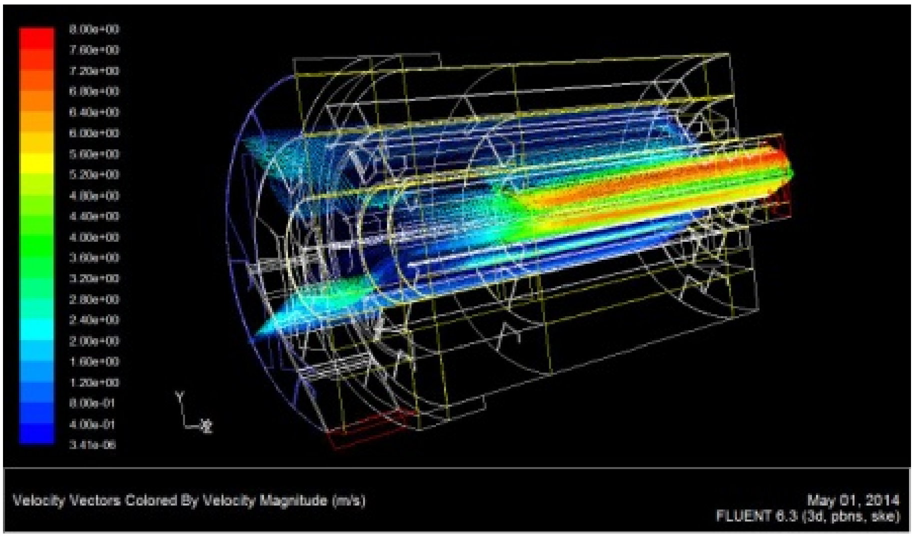
As the sieve was coming shorter either in the NRS and ES cases, the air ran along a longer way in MC before enter through the sieve into IC, as shown in figure 8.9.



FS case



NRS case



ES case

Figure 8.9. Air intake front of the external cylinder.

In IC the maximum air velocity was 0.3 m s^{-1} until it entered from MC, then the velocity raised to 5.5 and 7 m s^{-1} in the FS and ES cases respectively. In the NRS case, the velocity raised up to 2.5 m s^{-1} in the latter part of IC.

In EC, the air velocity was between 2.0 and 0.5 m s^{-1}, while in MC was between 1.0 and 2.0 m s^{-1} in all cases. Figure 8.10 shows the gross behavior of the air movement.

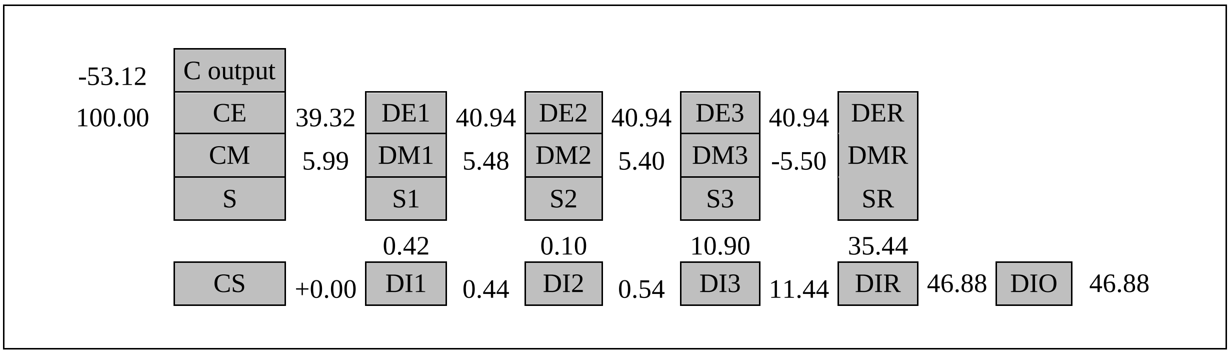
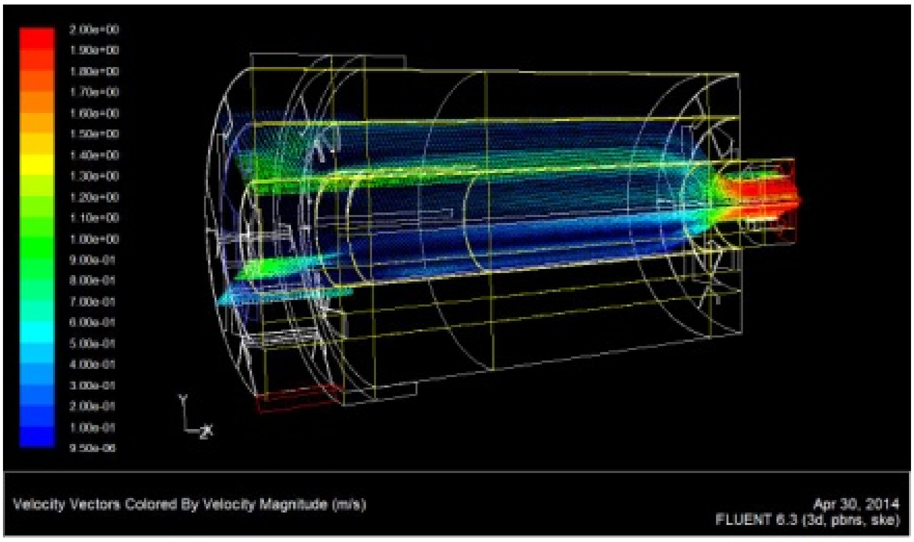


Figure 8.10. Mass Flow of air as percentage of the air intake. ECI and FS case.

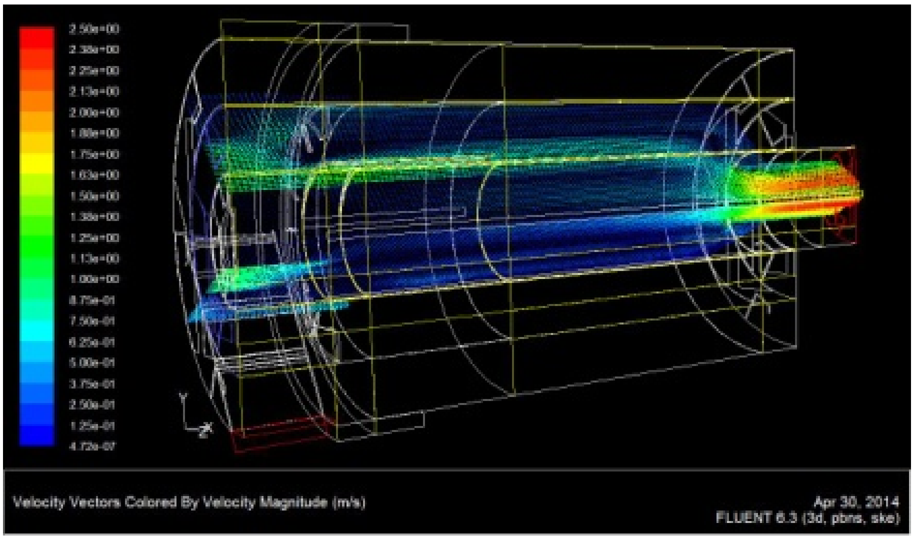
While 39.32 % of the air flowed to EC, just 5.99 % flowed to MC. In the return zone, 5.50 % of the air in the EC entered to MC. Then all this 35.55 % flowed into the internal cylinder through the sieve and 46.88 % leaved the dryer in the rear output. 53.12 % of the air leaved the dryer by the cover output without making contact with the grass.

8.5.3 Air in front of the Middle Cylinder Intake. MCI

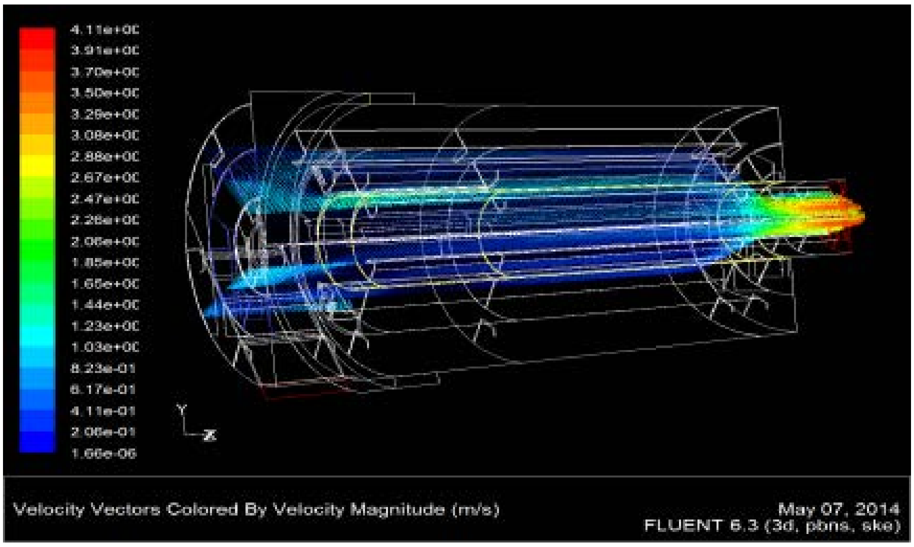
Better air distribution within all cylinders was obtained in the MCI case. In the inlet cover, the air was directed toward MC and EC scrolling them in the same direction. In MC, part of the air crossed the sieve towards IC especially at the end of the sieve. In all cases the speed of the air inside IC increased at the end of the sieve area. This velocity profile along the cylinder is shown in Figure 8.11. Figure 8.12 shows the gross flow of the air.



FS case



NRS case



ES case

Figure 8.11. Air intake front of the middle cylinder.

-26.75	C output											
	CE	40.50	DE1	40.50	DE2	40.50	DE3	40.50	DER			
100.00	CM	32.12	DM1	28.04	DM2	24.22	DM3	9.85	DMR			
	S		S1		S2		S3		SR			
			4.78		3.82		14.37		50.35			
	CS	-0.01	DI1	4.70	DI2	8.53	DI3	22.90	DIR	73.25	DIO	73.25

Figure 8.12. Mass Flow of air as percentage of the air intake. MCI and FS case.

In this case, thanks to the half barrier in the middle cylinder, 40.50 % of the flow entered to EC and 32.12 % to MC. From MC, small amounts of air were directed to IC through the sieve, and before the zone parallel to the return zone 22.90 % of air had entered. At the end 73.25 % of air leaved the dryer through the rear output, while 26.75 % leaved it from the cover without contact with the grass.

At the entrance of MC a circular half wall was implemented to prevent dripping of stems to the cover once they leaved the sieve of the IC. For this reason in this zone occurred an air divergence to the EC and a brake in air velocity, as seen in Figures 8.13 and 8.14.

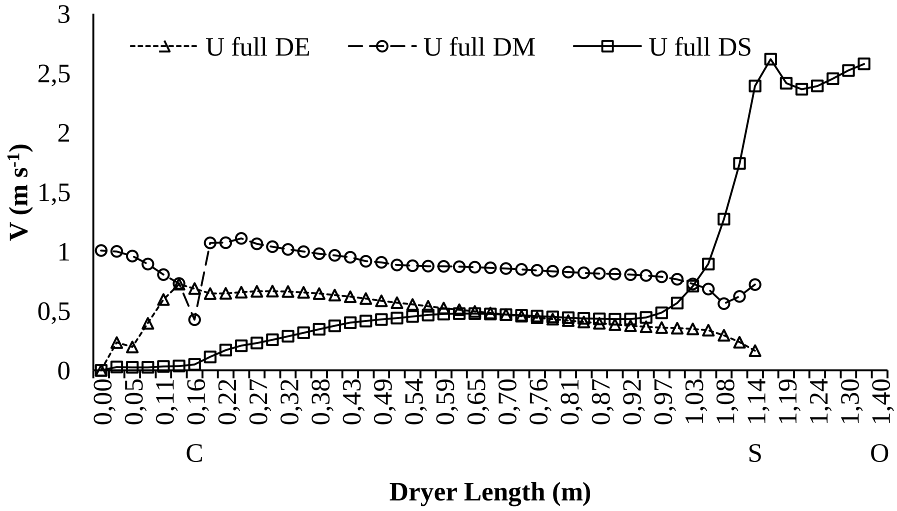


Figure 8.13. Air velocity profile in the three cylinders, MCI and FS case.
C: Cover, S: Sieve, O: Output.

These air velocity profiles were obtained in the half top of the dryer and away from the influence of the air outlet in the front cover.

In the FS case, air entered with velocities of 1.07, 0.65 and 0.11 m s^{-1} to the MC, EC and IC respectively. In IC air velocity was maintained between 0.20 and 0.55 m s^{-1} until air entered from MC, then the velocity raised up to 2.57 m s^{-1} at the outlet of the dryer. This case is presented as the best alternative.

Given these results, the best alternative was found when air enters in front of the middle cylinder and the sieve occupies the entire length of the inner cylinder.

For this case, the speed of the air was also analyzed in the lower half of the dryer and through the porous medium that corresponds to the grass.

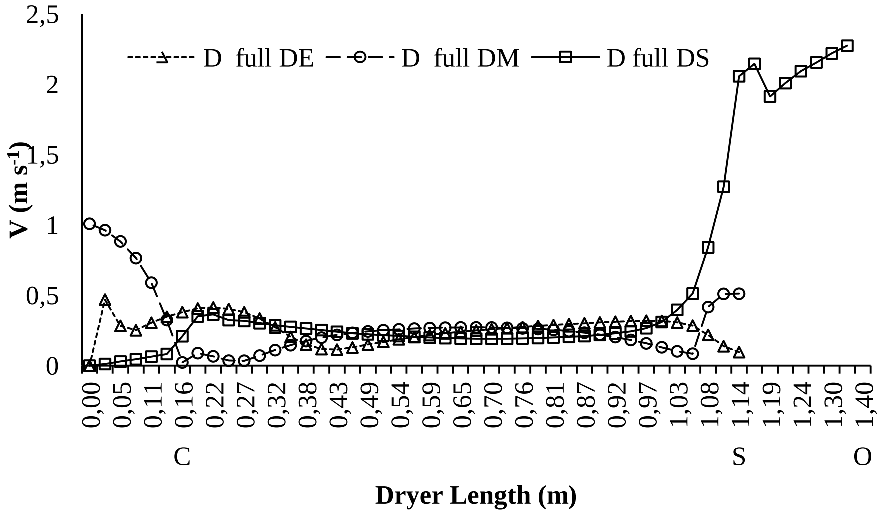


Figure 8.14. Air velocity profile in the lower half of the dryer. MCI – FS case.
C: Cover, S: Sieve, O: Output.

In the lower half of the drier, near ¼ of the air was directed toward the bottom outlet of the cover, so the air speed here was lower than in the upper half. From the start to the end of the cylinders the velocities did not chance much between 0.5 and 1 m s^{-1}. In the IC, the speed at the end, after the entry of air from the MC was similar to that in the upper half.

Finally, by observe the flow of air through the grass, the figure 8.15 at the top and bottom half was obtained.

To make this simulation, grass sections were modeled as if they were still, using bulk density values obtained by freely falling of the material in a container of known volume and without pressure. The grass that occupies the bottom of the cylinders and the one over the flights may be close to this value of density, but the grass in the cascade may have a lower value, and its parabolic drop velocity also affects the speed and air turbulence. However, this effect was not considered. Therefore the air speed values within the grass, were sampled in the grass on flights.

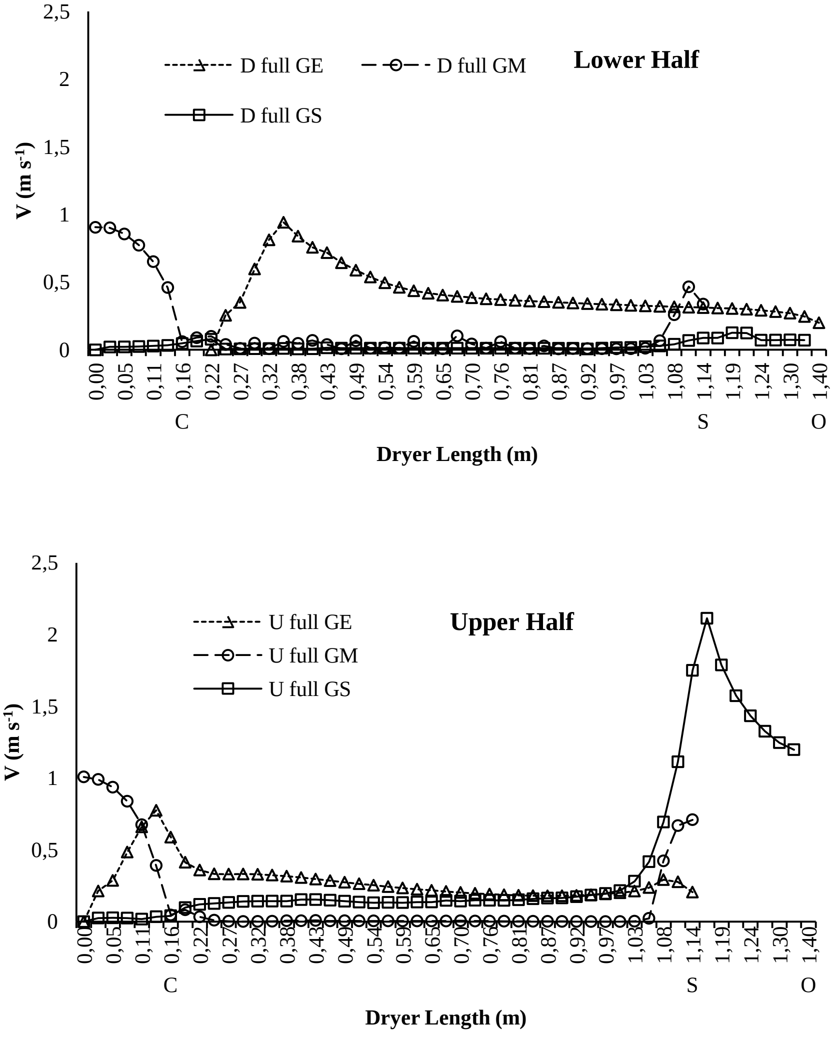


Figure 8.15. Flow of air through the grass. MCI and FS case.
C: Cover, S: Sieve, O: Output

There was no grass on the cover, this started in the cylinders, so a break in the air velocity at the 15 cm was seen. In the three cylinders the air velocity was less than the air speed out of the grass.

Given these assumptions in modeling, it was found that the velocity of air within the porous medium was lower than the terminal velocity values reported by [8.21].

In this case the picture of the air flow in the symmetrical plane that divides the dryer is shown in figure 8.16.

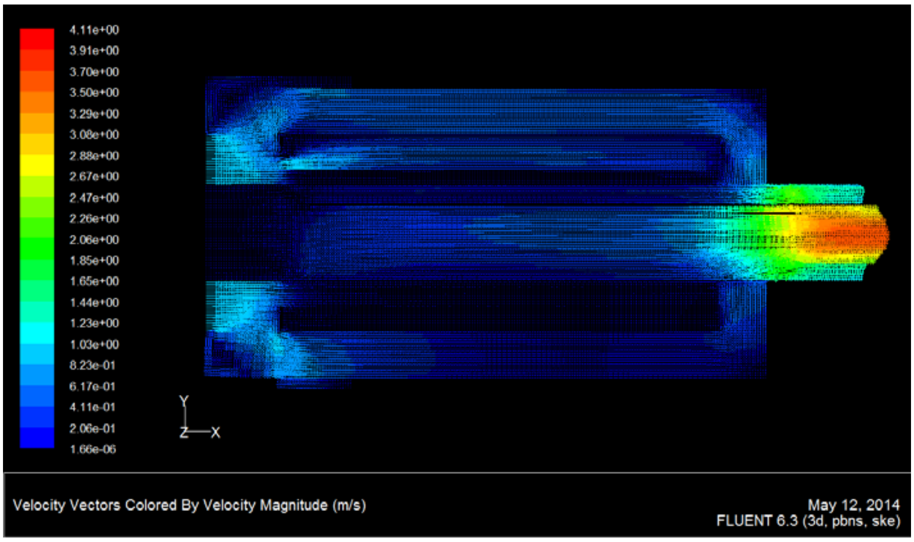


Figure 8.16. Air flow in a symmetric plane. MCI-FS case.

As figure 8.16 shows, in the areas occupied by grass, the air velocity was less than in those free of obstacles. The division of the air in front of the entrance is also clear; part went through the middle cylinder and part through the external one. At the end of the two more external cylinders there was a big transfer of air crossing the sieve to the internal path, and in this part the air velocity increased. Along the sieve, part of the air from middle cylinder passed to the internal one, through which it ran at small velocities.

8.6 CONCLUSIONS

A rotary dryer with three concentric cylinders has been devised, with a circular sieve in its internal cylinder for the drying of agricultural materials composed by stems and leaves like a mixture of Clover and Ryegrass. The function of this screen is enable the separation of leaves and stems to achieve ultimately a material with a homogeneous moisture content.

The path of the air in the cylinders of the dryer depends on the place of its input, since the sieve enables communication between the spaces of the middle and outer cylinder.

The output of stems, with also an air output in the initial cover, makes that some part of this air leaves the dryer without making contact with the plant material. Nevertheless, this output is necessary for the correct distribution of air in all the cylinders.

Taking in consideration this output, the array to achieve a better distribution and air velocity inside the dryer is when air enters through a ring in front to the middle cylinder in combination with a circular sieve that forms the total length of the inner cylinder.

With this option, the drying will be concurrent in the internal and middle cylinder and counter-current in the outer cylinder.

With an air inlet of 1 kg/s, the velocities in all the cylinders are lower than the drag velocity of the parts of the mixture.

For a next model, the rotational speed of the dryer and the movement of the material into this should be considered in order to model the drying of the material under these special conditions. For this, the equations describing the motion of the material in a rotating drum with flights, the material feed rate, and the drying curves for the components of the mixture are required.

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9 GENERAL DISCUSSION

Although the areas with pastures have reduced in recent decades in Europe against other forage crops, these crops still maintain a large area and require a significant amount of labour for both its production and its dehydration, which makes important continuing improve methods of drying.

In these composite plants, whose leaves and stems are those leaded to dehydration, there is a much larger number of stomata on the leaves than in the stems, the epidermis is also more pronounced in this latter. This explains, in part, why leaves dry first that stems. At the beginning of drying, resistance to the movement of water is lower in leaves that in stems, in this state the resistance through the cuticle is low, while the stomata resistance is high. Then the resistance to motion increases from the petiole to the leaves and these dry at a level that does not allow water to flow from the petioles. At the last moment the water exits by the stomata and cuticle and finally only through the cuticle. If leaves and stems are separated apart, the two elements dry more slowly because the loss of continuity.

In all cases the moisture content of the components of the mixture should be a below 0.2 g water g^{-1} dry mass in order to reduce the occurrence of mould and spoilage.

In the case of study, which is a mixture of Ryegrass and White Clover, differences in the drying behaviour between the two plants and between all components were found. However, the isotherms of components of Ryegrass were statistically similar. Although the differences are greater in the drying times and in the isotherms, these are minor with the enthalpy of vaporization. Therefore, this research was focussed in decreasing the difference in drying times, to achieve, at the end of the process, a mixture in which the moisture contents of the components were less heterogeneous.

The mechanisms more used for the dehydration of the pastures are the Rotary Dryers. In these, thanks to the cascade movement of material into the cylinders, and the low speeds of rotation, the material remains enough time to reach the desired moisture content.

For this reason the research focused on establish the rotary drying conditions that would lead to a drying and separation of the components bringing them to the desired moisture content, which must be below 0.2 g water g^{-1} dry mass.

Since in the dryer the pasture enters cut as chunks of a mixture of leaves, leaflet, stems and stalks and leaves together; a circular sieve inside the dryer makes the separation, so that the leaves, leaflet and stems plus leaves follow a route while the stems and ryegrass followed another, because these last two components have longer drying times.

Then for this, a dryer consisting of three concentric cylinders was proposed. A circular sieve forming part of the internal cylinder allows leaves to follow in this one, while stems and ryegrass pass the other two.

Within the dryer, the movement and the drying of the material is governed by the geometry of the flights, the rotational speed of the dryer, the length and geometry of the sieve, the slope of the dryer in the direction of feed and the temperature and velocity of air. Then each of these parameters was evaluated in order to find the best conditions that lead to a more homogeneous dry product.

The selection of the type of flight has been reported as very important for granulated materials, since most of the air should have contact with the material to dry. Inside of the grass dryer, the geometry of the flights have not a big influence on the drying time of the components of the mixture.

The rotational speed of the dryer has some influence on the reduction of the difference in drying times. It was found that, at higher speeds of rotation a more homogeneous material. Nevertheless, there is a critical speed of rotation, after which the centrifugal force prevents the correct fall of the material from the flights. The tests showed that 3.14 s^{-1} is the best rotary speed for the dryer, however all commercial grass dryers operate at speeds below 1.05 s^{-1}. This is because the rotational speed determines the residence time of material in the dryer, and at faster rotary velocities, the material moves faster. In addition, the granulated materials have characteristics of flow and movement different from the grass.

In other hand, the temperature of the drying air has the greatest influence on the reduction of the differences in drying times, since at the higher tested temperature, 80°C, the differences were of maximum 3.3 h when the screen turns at 1.57 s^{-1}.

With a combination of air at 80°C and 3.14 s^{-1}, after cloverleaves have reached 0.2 g water g^{-1} dry mass, stems takes even 111 minutes more and the grass 6 minutes more to get the same moisture content. After this time, the leaves have reached 0.01 g water g^{-1} dry mass, condition at which there is crumbling. While at 1.57 s^{-1}, cloverleaves reach 0.2 g water g^{-1} dry mass at the 96 min, at 216 min stems and the grass at 108 minutes. At this time the leaves have reached 0.01 g water g^{-1} dry mass.

The flow of air in the interior of the dryer has a great influence on the movement of material. It is important to set the rate and the right direction of air to allow the desired movement of material and, since there is a sieve to separate the leaves, a pressure that attach the leaves to the sieve should be avoided.

In addition, since the material inside the dryer is changing its moisture content, the terminal velocity and drag coefficients has been calculated for different conditions. It was determined that especially leaves vary their projected area and, like all components of the mixture, their density as they lose moisture, which should have an influence on the design of the flights in the stages of the dryer.

Terminal velocity values decline as components lose moisture, while for White Clover Leaves there were no significant differences of this velocity between moisture contents, these differences were more notorious for White-Clover Stems and Ryegrass.

The setup of the dryer must allow that the material progress because of the inclination of the flights but not because the speed of the air. The terminal velocities of components and its drag coefficients are so low, even in fresh, that high air speeds cause that material exits the dryer much before the time required to reach the desired moisture content.

Thus, for fresh material entering to the dryer, air speeds should be less than 1.5 m s^{-1}, or with *Re* of airflows less than 790, to avoid drag leaves to inner cylinder. At the entrance of the middle cylinder the air speed must be less than 3.37 m s^{-1} or with Re below 29000, to avoid the drag of fresh Clover Stems and Ryegrass.

When materials have come almost to their final moisture, close to 0.2 g water g^{-1} dry mass, the Re number of the air must be less than 600 for the White Clover Leaves and to 7000 - 8000 for the White Clover Stems and Ryegrass.

Finally, a flow of air passing through the sieve from the inner towards the middle cylinder should be avoided, because this would mean that leaves stick to the sieve, with which the output of Clover Stems and Ryegrass is blocked and the Clover Leaves do not flow fluently along the inner cylinder.

One of the distinguishing points of this proposal for a rotary dryer is the sieve, this communicates the Middle Cylinder with the Internal Cylinder in such a way that through it should flow only the clover stems and the Ryegrass while the leaves remains in the inner cylinder. Furthermore, there is a flow of air between these two cylinders.

Since a good separation of the clover stems and ryegrass for all the moisture contents of the mix was found, the sieve can be prolonged along the entire length of the internal cylinder, getting that all the stems and ryegrass are separated from the leaves. For this, the advance speed of the material inside the rotary drum is also considered: At 1 sec^{-1} of rotation, a very good separation of the material is achieved, with the advantage that the advance rate is low and larger residence times of leaves inside the dryer are available. At this same low rotation speed, the greater retention of leaves inside the sieve is achieved. For the diameter of the test sieve, 40o mm, the adequate rotation speed should be between 2.5 and 3.7 sec^{-1} according to the literature. However, the best speed was 1 sec^{-1}. This rotation speed must be adjusted to the size of the sieve - inner cylinder in the dryer.

As the material dries, becomes a greater flow of fine material through the sieve. This material will take the path of the stems, where it will suffer even more dried, with the possibility of becoming into dust. Measures to prevent pollution to the atmosphere with these particles should be taken.

According CFD analysis of a dryer prototype, the entire length of the inner cylinder must be a sieve, so the air is evenly distributed in the best way on three cylinders. The best air distribution is achieved when the air enters from the cover of the dryer through a ring shaped hole in front of the middle cylinder. In this way, air enters to the inner cylinder from the middle cylinder through the sieve and prevents the sticking of leaves to the screen.

In order to set this division of the air flow, also in the entrance of the middle cylinder should be a circular ring, which serves to avoid the dripping of the clover stems and ryegrass to the initial cover when they come out from the inner cylinder - sieve. This ring makes the air deflects towards the outer and middle cylinders.

10 GENERAL CONCLUSIONS

A mixture of ryegrass and white clover is an useful example to evaluate the behaviour of drying of various components, which, in the vegetative stage, are mainly leaves and stems.

Due to their physiology, the process of drying occurs more quickly in the leaves than in the stems. This is due to their higher concentration of stomata, a thinner cuticle, higher ratio area/content moisture, and a lower water vapour output resistance.

Some characteristics are changing along the drying; these are also different between the components of the mixture, namely:

- Drying Rate in thin layer and in rotation.
- Bulk density.
- Projected area
- Terminal velocity.
- weight/Area Ratio.
- Flux through a rotary sieve.

Each of these features is described by different parameters, which allow modelling their changes throughout the drying and making comparisons between the components of the mixture.

Within the studied parameters of drying, the speed of drying of White Clover Leaves, White Clover Stems, White Clover chop and Ryegrass is a function of:

- Temperature of the drying air.
- Speed of rotation of a cylinder with flights.

The separation that should be made in the grass mixture is: on one hand the leaves of White Clover and on the other, White Clover Stems and Ryegrass.

White Clover Leaves dried faster and the White Clover Stems slower than all the components of the mixture. The differences in drying time are lower when the drying air is at 80°C, which was the highest temperature studied.

When the drying is made in a rotary dryer with lifting flights, rotating at 30 rpm, which was the highest studied rotational speed, the higher drying rates of all components were found. Above this rotation speed, the centrifugal force is equal to or greater than the weight and there is not a correct movement of the material inside the dryer.

With a combination of a rotation at 30 rpm and drying air at 80 °C the maximum difference in the required time to carry the mixture components to moisture content of 0.1 g water g^{-1} dry mass is 1.46 h.

Taking into account the differences in the projected area and flow through a sieve that shows each of the components, these can be separated using a rotary sieve.

The separation between the stems, ryegrass and leaves of the mixture through a rotating sieve can be made along the drying for all the moisture contents; however, it is better when the material is dry.

All the components of the mixture have a different terminal velocity, which, in addition, varies with the moisture content. Taking into account this feature, the major differences are found when the material is fresh. This behaviour allows making a separation of the components using a vertical stream of air.

It is advisable making the separation of the components using the terminal velocity, when the material is fresh, because they require turbulent airflow with high Reynolds, which are easier to establish than laminar flows, which belong to the terminal velocity of the driest states of material.

A rotary dryer with three concentric cylinders, whose inner cylinder consists of a sieve, allows the drying and separation of the components of the mixture. Thanks to the action of separation of the sieve, the leaves follow the path of the inner cylinder while the stems and ryegrass follow a longer route through the middle and external cylinders.

Within the values of the evaluated parameters, the best conditions of functioning of this dryer are:

- Rotational speed: 10-15 rpm.
- Air temperature: 80 ° C.
- Airflow: to ensure that the air speed at the entrance of the inner cylinder be maximum 1.5 m s^{-1}, and at the middle and outer cylinders entrance to be maximum of 3.37 m s^{-1}.
- Air intake: A circular ring on the cover of entrance that has the same area, and is located in front of the Middle cylinder.
- Two outputs for the air and material must be provided: One at the end of the internal cylinder - sieve for the dry leaves and another at the bottom of the frontal cover, for the stems, grass and air.

Although the best drying conditions are obtained with a rotational speed of 30 rpm, it is best to use a speed of 10-15 rpm, and a long sieve, which gets greater separation of stems and ryegrass from the leaves and a greater residence time on all cylinders.

Definitely, it is technically possible to develop a rotary dryer and make the separation of the components (stems, leaves) of a mixture of grass, in which the residence time of each of the components is close to the that necessary to allow to dry them until the desired moisture content. This would avoid the problems of high moisture contents allowing the formation of fungi or over-drying.

11 SUMMARY

In composite agricultural materials such as grass, tee, medicinal plants; leaves and stems have a different drying time. By this behavior, after leaving the dryer, the stems may have greater moisture content than desired, while the leaves one minor, which can cause either the appearance of fungi or the collapse of the over-dried material.

Taking into account that a lot of grass is dehydrated in forced air dryers, especially rotary drum dryers, this research was developed in order to establish conditions enabling to make a separation of the components during the drying process in order to provide a homogeneous product at the end. For this, a rotary dryer consisting of three concentric cylinders and a circular sieve aligned with the more internal cylinder was proposed; so that, once material enters into the dryer in the area of the inner cylinder, stems pass through sieve to the middle and then continue towards the external cylinder, while the leaves continue by the inner cylinder.

For this project, a mixture of Ryegrass and White Clover was used. The characteristics of the components of a mixture were: Drying Rate in thin layer and in rotation, Bulk density, Projected Area, Terminal velocity, weight/Area Ratio, Flux through Rotary sieve.

Three drying temperatures; 40°C, 60° C and 80° C, and three rotation speeds; 10 rpm, 20 rpm and 40 rpm were evaluated. It was found that the differences in drying time are the less at 80 °C when the dryer rotates at 40 rpm. Above this speed, the material adheres to the walls of the dryer or sieve and does not flow.

According to the measurements of terminal velocity of stems and leaves of the components of the mixture, the speed of the air should be less than 1.5 m s^{-1} in the inner drum for the leaves and less than 4.5 m s^{-1} in middle and outer drums for stems, in such way that only the rotational movement of the dryer moves the material and achieves a greater residence time. In other hand, the best rotary sieve separation efficiencies were achieved when the material is dry, but the results are good in all the moisture contents. The best rotary speed of sieve is within the critical rotational speed, i.e. 20 rpm. However, the rotational speed of the dryer, including the sieve in line with the inner cylinder should be 10 rpm or less in order to achieve the greatest residence times of the material inside the dryer and the best agitation through the use of lifting flights.

With a finite element analysis of a dryer prototype, using an air flow allowing speeds of air already stated, I was found that the best performance occurs when, through a cover, air enters the dryer front of the Middle cylinder and when the inner cylinder is formed in its entirety through a sieve. This way, air flows in almost equal amounts by both the middle and external cylinders, while part of the air in the Middle cylinder passes through the sieve towards the inner cylinder. With this, leaves do not adhere to the sieve and flow along drier, thanks to the rotating movement of the drums and the showering caused by the lifting flights.

In these conditions, the differences in drying time are reduced to 60 minutes, but the residence time is higher for the stems than for leaves, therefore the components of the mixture of grass run out of the dryer with the same desired moisture content.

12 ZUSAMMENFASSUNG

In landwirtschaftlichem Material wie Gras, Tee oder Heilpflanzen haben Blätter und Stengel unterschiedlich lange Trocknungszeiten. Auf Grund dieses Umstandes können die Stengel, nachdem sie aus dem Trockner kommen, eine größere Feuchtigkeit beinhalten als gewünscht, während die Blätter eine geringere haben, was entweder zur Bildung von Pilzen oder zum Zerfall des zu trockenen Materials führen kann.

Wenn man in Betracht zieht, dass ein große Menge Gras in Umlufttrockern dehydriert wird, insbesondere in Rotationstrocknern, so wurde diese Studie mit dem Ziel entwickelt, die Bedingungen festzulegen, unter denen eine Trennung der Komponenten während des Trocknungsprozesses möglich ist, so dass ein homogenes Endprodukt geliefert werden kann. Dafür wird ein Rotationstrockner bestehend aus drei konzentrischen Zylindern und einem kreisförmigen Sieb, das mit einem weiteren internen Zylinder verbunden ist, vorgeschlagen. Sobald das Material in den Bereich des inneren Zylinders gelangt, passieren die Stengel durch das Sieb in die Mitte, und von dort aus kommen sie in den externen Zylinder, während die Blätter im inneren Bereich verbleiben.

Für dieses Projekt wurde eine Mischung aus Weidelgras und Weißklee verwendet. Die Charakteristiken der Komponenten dieser Mischung waren: Trockenrate in dünnen Schichten und in Drehbewegung, Rohdichte, projizierte Fläche, Endgeschwindigkeit, Leistungsgewicht/Flächenverhältnis, Fluss durch Rotationssieb.

Es wurden drei Trocknungstemperaturen (40°C, 60°C und 80°C) und drei Rotationsgeschwindigkeiten (10 rpm, 20 rpm und 40 rpm) untersucht. Dabei wurde herausgefunden, dass die Unterschiede in der Trocknungszeit bei 80°C und bei einer Rotation von 40 rpm am geringsten ausfielen. Bei einer höheren Geschwindigkeit bleibt das Material an den Wänden des Trockners oder des Siebs haften und bewegt sich nicht weiter.

Gemäß den Messungen der Endgeschwindigkeit der Stengel und Blätter der Mischungskomponente sollte die Luftgeschwindigkeit für die Blätter weniger als 1.5 m s-1 in der inneren Trommel betragen, und weniger als 4.5 m s-1 für die Stengel in der mittleren und äußeren Trommel, so dass nur die Rotationsbewegung des Trockners das Material bewegt und dadurch eine größere Residenzzeit erreicht wird. Andererseits wurden die besten Rotationssieb-Wirkungsgrade bei trockenem Material erreicht, wobei die Ergebnisse bei allen Feuchtigkeitsgehalten gut waren. Die günstigste Rotationsgeschwindigkeit des Siebs war innerhalb der kritischen Drehzahl, d.h. 20 rpm. Dennoch sollte die Rotationsgeschwindigkeit des Trockners, das Sieb mit dem inneren Zylinder inbegriffen, weniger als 10 rpm betragen, damit ausreichend lange Residenzzeiten des Materials im Trockner und die beste Bewegung bei abhebenden Partikeln erreicht werden.

Mit einer Finite-Elemente-Analyse des Trocknerprototyps und einem Luftstrom mit vorgegebener Luftgeschwindigkeit wurde herausgefunden, dass die beste Leistung erzielt wurde, wenn Luft durch einen Deckel, in die Vorderseite des mittleren Zylinder gelangt und wenn der innere Zylinder gänzlich durch das Sieb geformt ist. Auf diese Weise gelangte Luft in beinahe gleichen Mengen sowohl durch die mittleren als auch die äußeren Zylinder, während ein Teil der Luft aus dem mittleren Zylinder durch das Sieb zum inneren Zylinder gelangt. Auf diese Weise haften die Blätter nicht an dem Sieb und bewegen sich in trockenerem Zustand durch die Rotationsbewegung der Trommel und dem Niederfallen, das durch die abhebenden Partikel verursacht wird.

Unter diesen Bedingungen wurden die Unterschiede in der Trocknungszeit um 60 Minuten reduziert, wobei die Residenzzeit für die Stengel länger war als für die Blätter, so dass die Komponenten der Grasmischungen mit dem erwünschten gleichen Feuchtigkeitsgehalt aus dem Trockner kamen.