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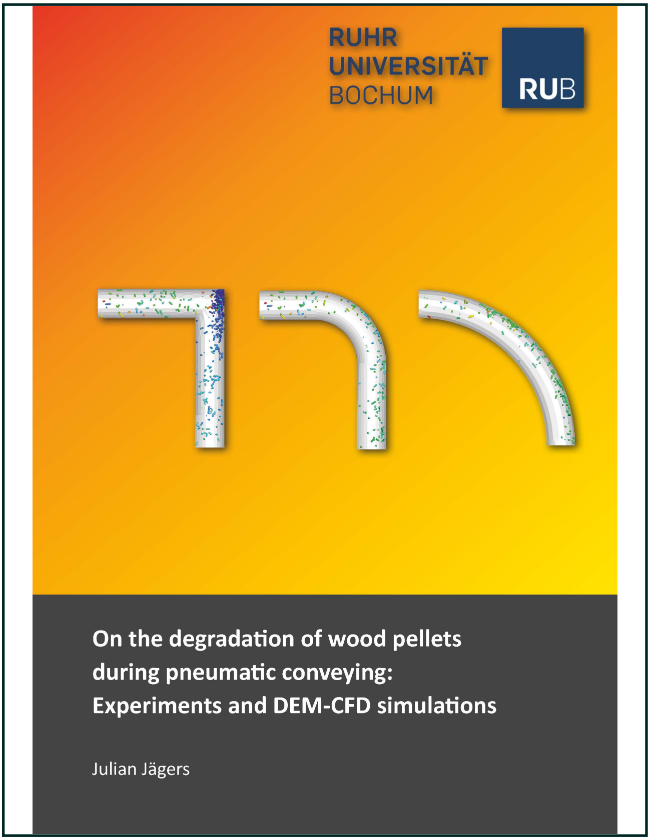
On the degradation of wood pellets during pneumatic conveying: Experiments and DEM-CFD simulations



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1 Introduction

Apart from solar, wind and hydro power, solid biomass is the most commonly used renewable energy resource [10]. Due to its availability and security of supply regardless of seasonal and weather conditions, wood plays a decisive role in the CO_2-neutral energy supply for heat and power generation. Wood pellets belong to the most established and widespread commercial types of woody biomass fuels [54]. The pellets made of dried, mainly untreated wood allow for the value-creating usage of industrial wood and saw mill waste. Due to their good handling and storage characteristics, high energy density and comparatively homogeneous particle sizes and shapes, wood pellets are highly suitable for industrial heat and power generation as well as for decentralised domestic heat generation by automatically fed small-scale combustion systems. Figure 1.1 provides an overview of worldwide wood pellet production and consumption in 2018 compared to 2017.

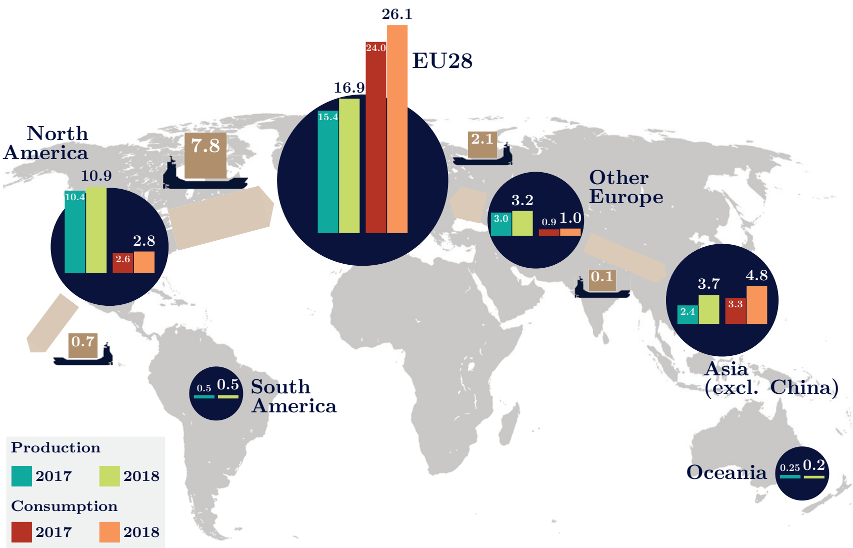

Figure 1.1: World pellet map and trade flow in 2018 (million tonnes) [35]

It confirms the current dominance of the European countries (EU28) concerning wood pellet consumption, but according to statistics of the European Pellet Council (EPC), Asia's market grows rapidly and becomes the driving force behind the development of the global wood pellet market alongside EU28 [35]. The European Union imports wood pellets mainly from USA or Canada and from neighbouring European countries (primarily Russia). The central European demand is significantly driven by industrial consumption in the UK, Denmark and Belgium [174]. Nevertheless, the residential heating sector accounts for 55 % of the required wood pellets, which is the larger share compared to the industrial sector [173]. Within EU28, the EPC expects an increase of woody biomass availability by the growth of fast-growing plants [35]. Note that in the present thesis the word *pellet* is always in reference to *wood pellet* unless otherwise stated.

1.1 Motivation

After pelletising, wood pellets pass various transport and storage procedures. Therein, they undergo different mechanical loads which lead to degradation through abrasion and breakage. Thus, the bulk's content of fines (according to EN 15234-2 particles with a size <3.15 mm [25]) is increased. Especially the transportation steps between the individual storage facilities cause high mechanical loads. According to Mina-Boac et al. [153], wood pellets are transported, retrieved or stored at least eight times on their way from production to combustion. For the route from production in British Columbia to thermal conversion in Europe, Oveisi et al. [167] even assume an average number of ten of so-called handlings. Not only for industrial but also for domestic purposes wood pellets are often conveyed pneumatically. In particular, these processes at various steps of the production and supply chain can cause significant pellet degradation, which is indicated exemplary in experiments by Wiese [233] or Wiese et al. [232], Abdulmumini et al. [3] and in studies of IEA Bioenergy [99].

There exist various reasons for avoiding pellet degradation and thus the increase of fines. In some cases, very small particles are produced and emitted as airborne dust, which can be explosive and is therefore highly relevant for safety aspects. Further, an increased amount of fines favours dust emissions from furnaces, which are potentially harmful to human health and are therefore limited e.g. in Germany by the Federal Immission Control Act (BIMSchV) [159]. The dangers of emission of harmful organic particulate matter and bioaerosols during loading and unloading of pellet delivery vehicles are discussed in the IEA Bioenergy studies [99]. In addition to safety and health aspects, higher amounts of fines play a decisive role concerning undisturbed domestic facility operation. For example, high fines contents can cause blocking of fuel supply devices like screw conveyors or suction probes. Moreover, the accumulation of fines caused by repeated silo loading and unloading processes reduces the domestic storage capacity and thus requires more maintenance [160].

Pneumatic conveying is one of the established transportation methods for wood pellets [54]. A problem in practice is that ideal conveying conditions can rarely be achieved. For example, plug flow conveying, which is considered as the most gentle way of pneumatic transport, is rarely applied due to high risk of blockages and its complex technical implementation during instationary deliveries by silo trucks [151]. Especially the conditions of the final delivery process to domestic storages vary considerably. On the one hand, the conveying conditions depend on local circumstances like hose length, shape and number of bends as well as the storage geometry. On the other hand, the actual operational parameters like air and product mass flows are manually set by operating staff and thus differ as well [48]. Despite the high quality of the mainly EN*plus*-certified pellets (comply high quality standards with a low amount of fines), operational problems can still occur due to generation of fines by inappropriate selection of pipe components or operating parameters during pneumatic conveying.

1.2 Objective and outline

The primary aim of the current thesis is to investigate the dependence of wood pellet degradation and fines formation during pneumatic conveying on operating conditions like air and product mass flow or shape of pipe components. The size reduction of the cylindrical pellets during pneumatic transport caused by mechanical impacts is analysed both experimentally and numerically. For detailed insights into occurring breakage mechanisms, particle-resolved data (e.g. contact frequencies, collision velocities and angles, etc.) are mandatory. As a central numerical tool, the in-house Discrete Element code (DEM) of the Department of Energy Plant Technology (LEAT) of the Ruhr-University Bochum (RUB) is applied. This DEM code determines the particle-particle and particle-wall interactions together with the particles' exchange of momentum with the particle-surrounding fluid phase. For considering the interactions of fluid phase and particles, the DEM code is coupled with a commercial Computational Fluid Dynamics (CFD) solver (ANSYS Fluent®). For numerical assessment of pellet degradation during pneumatic conveying, the existing DEM code is extended by an empirical degradation model, containing statistical functions for breakage probability and size distribution of the resulting fragments. Thus, direct modelling of particle degradation and the subsequent interactions of particles, fragments and the surrounding fluid phase in dependence of varying operating parameters is achieved. The accuracy of the model developed is assessed by comparison of results of coupled DEM-CFD simulations and corresponding experiments performed with varying operating conditions and shapes of common pipe components.

Furthermore, resulting pressure losses, which play a decisive role in design and dimensioning of conveying lines or operating conditions are investigated experimentally and determined numerically, respectively. Thus, important insights are obtained to give recommendations regarding critical components or operating conditions and thus reduce the risk of blockages.

Apart from degradation behaviour and prevailing pressure losses, the numerical approach allows detailed insights into the motion of complex-shaped poly-disperse particles, flow profiles and mechanical wall stresses during pneumatic conveying processes.

The current thesis is divided into seven parts. **Chapter 2** starts with essential basics regarding both wood pellets and pneumatic conveying and gives an overview of the current state of research. **Chapter 3** describes the applied numerical approaches of DEM and CFD. The implemented models of both solid and fluid phase are explained, before the applied momentum-coupling scheme between both phases is discussed in more detail. **Chapter 4** deals with the degradation characteristics of single particles due to collision with a target plate. Single particle impact tests are performed to develop empirical functions for statistical description of breakage probability and size distribution of the resulting fragments in dependence on parameters like initial particle length, collision angle and velocity. The model developed and implemented in the in-house DEM approach serves as the basis for the following numerical simulation of particle degradation effects of pneumatic conveying processes. Experimental and numerical results of the single particle impact tests and thus the validity of the developed breakage model are finally compared or discussed, respectively. **Chapter 5** describes both the experimental and numerical setup for the investigation into pneumatic conveying of wood pellets, focused on the influence of varying conditions on particle size reduction. Furthermore, numerical models and corresponding model parameters applied for determination of inter-particle and particle-fluid interactions are verified. In **chapter 6**, experimental and numerical results of the investigation into pneumatic conveying processes are discussed. The impact of the shape of different pipe components and the influence of varying operating conditions on particle motion and fluid phase behaviour, as well as on the wall or particle stresses (and thus the particle size reduction) are described. Additionally, the suitability of the numerical degradation model developed for predicting size reduction effects during pneumatic conveying is examined on application. In **chapter 7**, the implemented degradation model and the individual numerical and experimental results are summarised conclusively. The thesis finishes with an outlook on further fields of application and potential approaches for improvement.

Within the framework of the current thesis, publications were made [a–j]. The findings of these publications are summarised in this contribution and expanded to unpublished results.

2 Basic principles and state of the art

2.1 Wood pellets as biomass fuel

Requirements for solid biomass for energy generation are basically defined in the standards ISO 16559 [31] and ISO 17225 [26–29, 32–34]. In general, these standards distinguish six classes of biomass derived fuels (wood pellets, wood briquettes, wood chips, logs, non-woody pellets and non-woody briquettes).
According to ISO 16559 [31], wood pellets are defined as a fuel pressed from pulverised biomass with or without additives, usually cylindrically shaped with broken edges and a length between 3.15 and 40 mm. Due to the specifications defined by ISO 17225-2 [33], only pellets with a diameter between 6 and 8 mm are authorised for use in small and medium scaled firing systems. All classes of biogenic solid fuels, which are classified according to ISO 17225-1 [32] on the basis of origin and source, can be used as raw material for wood pellet production. This includes woody or straw-like biomass, biomass of fruits and mixtures of both. In accordance to the focus of the current thesis, figure 2.1 provides only the subclasses of woody biomass.

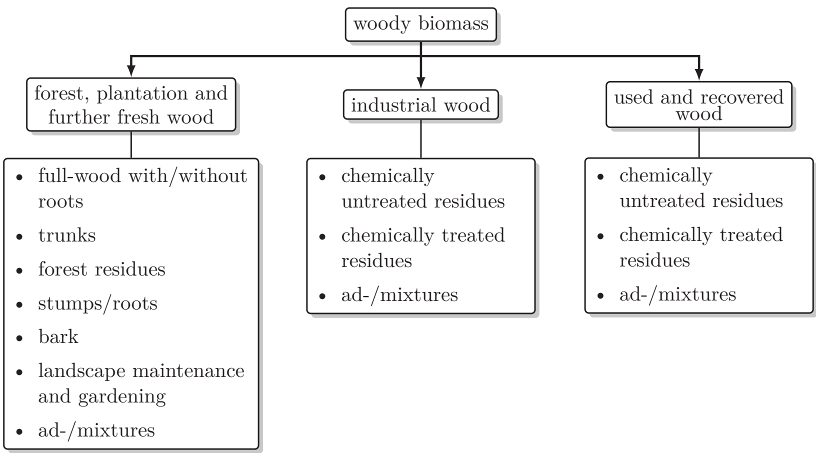

Figure 2.1: Classification of woody biomass according to ISO 16559 [31]

The chemical composition and thus the properties of the pellets vary significantly depending on the pellet mill and its location, the ratio of hardwood to softwood, the mixture of species and chip sizes (branches vs. wood chips vs. sawdust, etc.). For example, a pellet mill in Southampton (Virginia, USA) purchases 100 % of hardwood types, while another mill in Cottondale (Florida, USA) processes mainly softwood types for the production of wood pellets [127]. Pellet plants located geographically close together provide relatively comparable ratios of hard- and softwood [202]. In Central Europe, mainly chemically untreated industrial wood without bark, by-products of the wood-working and processing industry in form of chips, wood flour or cross-cut wood are used for production of wood pellets. Industrial logs are only used as raw material for pellet production in addition to sawmill residues. However, a future increase in demand for biofuels is generally expected (cf. chapter 1), so further biomass potentials have to be developed and the use of round logs will increase [54].

Compared to other biomass fuels, wood pellets can easily be specified and classified. The raw materials available for wood pellet production are regulated by quality standards according to ISO 17225-2 [33]. Based on this standard, a distinction is made between three different qualities EN*plus*-A1, EN*plus*-A2 and EN*plus*-B. These are based on the certification schemes EN*plus* and EN, developed by the German Wood Fuel and Pellet Association (DEPV) and launched in 2010 by the European Pellet Council, which is working under the European Biomass Association (AEBIOM) [69]. The EN*plus*-certification scheme sets certain standards for pellet production, quality assurance, labelling, logistics, intermediate storage and delivery to the customer. EN*plus*-certified pellets must comply with the limits of the properties to be checked. For instance, the certification system sets limiting values for water and ash content, as well as ash softening temperature and the shares of further additives and species:

- **EN*plus*-A1** Pellets from logs or chemically untreated residues with low contents of ash (0.7 %) and nitrogen (0.3 %),
- **EN*plus*-A2** Pellets made of full-wood or forest residues and bark with slightly increased contents of ash (1.2 %) and nitrogen (0.5 %),
- **EN*plus*-B** Industrial wood and chemically untreated used wood with high contents of ash (2.0 %) and nitrogen (1.0 %).

Both ash and nitrogen contents are limited, since the emissions of dust and nitrogen oxides directly correlate with these values. Additionally, an increased amount of ash requires a special ash removal system and generally implies an increased risk of slag formation and corrosion in biomass boilers [37]. However, in all three cases the certified pellets contain a maximum of 1.0 wt.-% of fines when leaving the last step of loading [6]. Due to the limitation of raw materials in the highest quality level (EN*plus*-A1) to debarked round wood and chemically untreated sawmill residues, this class is mainly relevant for domestic purposes. With decreasing quality level, the permitted range of raw materials and the limiting value for the ash content increase, which results in reduced ash softening temperatures. Thus, the use of both quality grades EN*plus*-A2 and EN*plus*-B is mainly limited to the industrial sector [154]. Depending on the season and weather conditions, the water

content of freshly harvested wood can be up to 60.0 wt.-%. Hence, a further important quality criterion for pellets in all three EN*plus*-classes is the prescribed maximum water content of 10.0 wt.-% [33].
Although, from a technical point of view, all biogenic solid fuel classes are suitable for the production of wood pellets, the quality of the pellets is largely dependent on the raw material used. Döring [54] provides a detailed overview of the influences of individual parameters on pellet quality. In summary, the mass fractions of the three biopolymers lignin, cellulose and hemicellulose are decisive for the carbon content of the raw material and thus the energy content related to the dry mass. The content of cellulose and hemicellulose influences the drying properties of the raw material. The proportion of lignin, which is also used as a natural binder, influences the mechanical durability (DU) of the pellets, which is a quality factor within EN*plus*-certification scheme [36].
The DU of wood pellets is defined as the resistance to any size reduction due to mechanical impacts during transport, loading and storage [74]. It is affected by a number of parameters, such as raw material, chip size, production process, water content and the use of binding. The durability is usually determined in a standardised procedure according to EN ISO 17831-1 [30] with a so called tumbling box tester and is defined as the ratio of the sieved mass of the sample before (m_0) and after (m_1) the test procedure:

$$DU = \frac{m_1}{m_0} \cdot 100 \qquad [\%] \qquad (2.1)$$

Commonly, this value deals as a first reference of the amount of fines that may be produced by mechanical impacts during handling [73]. To obtain EN*plus*-A2 and EN*plus*-B-certification, the mechanical durability of the wood pellets must be at least 97.5 %. Even stricter criteria apply for EN*plus*-A1-certification ($DU \geq 98.0\,\%$) [49].

2.1.1 Production process

The pelletising technology used for the production of wood pellets has its origins in Canada and was adapted to European market requirements in the 1990s. As already mentioned, biomass pellets are produced from a wide variety of raw materials and have a wide range of applications today, ranging from individual fireplaces to central heating systems up to the use in industrial power plants [141]. Due to heterogeneous wood species, varying size of the chips and the different water content, the wood used must be prepared before pelletising. The integration of the necessary preparation steps into the process chain of pellet production from sawdust is depicted in figure 2.2 exemplarily.

Depending on the intended application, there exist quality criteria for the final product, which, among others, determine the limits of respective ingredients. In this context, the focus is not only on reducing emissions but, for example, also on preventing corrosion of the firing system. For this reason an initial analysis of the raw material is necessary before production. Furthermore, the production methods used for debarking, drying and crushing depend on the raw material and its composition, e.g. the water content. In Germany, the initial raw materials with an average water content between 35 to 45 % (e.g. sawdust) are mostly dried in belt dryers, which reduces the water content to 10 to 14 % [139]. Subsequently, the dry raw material is crushed within hammer mills to achieve a uniform particle size distribution. For many applications, a comminution next to 1 mm below the end product diameter has been determined as suitable [133].

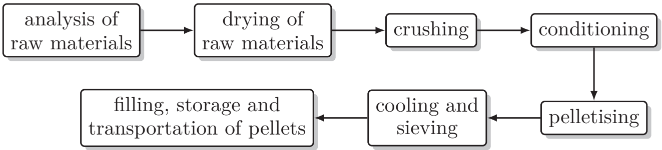

Figure 2.2: Steps of pellet production process [105]

In addition to a uniform product quality, the milling process leads to an increase of the specific raw material surface. Thus, the natural binder lignin can be better split up during pelletising. Next, the biogenic raw material is conditioned to improve the general binding properties. Depending on the water content, the crushed biomass is moistened to ensure a water content between 10 and 15 %. For improving the durability of the final product and reducing friction inside the pelletiser, auxiliary materials or additives can be added to the raw material in the conditioner or even before in the hammer mill. Subsequently, the conditioned raw material is pressed into pellets. For this purpose edge mills with flat or ring dies are usually applied. The pressure inside the edge mill and increased temperatures (up to 298 K) resulting from friction activate the adhesion capability of the lignin, which coats the cellulose fibers and binds the initial raw material to a stable end product. For fast solidification and ensuring dimensional stability, the pellets are cooled down to ambient temperature (about 25°) [140]. Finally, the residual material is separated by vibrating sieves [59].

2.1.2 Domestic delivery and storage procedure

Detailed insights into the entire (global) supply and process chain of wood pellets including raw materials treatment, pelletising process and final delivery steps are provided by Hughes et al. [98], Boukherroub et al. [18] and Uasuf [221]. In accordance to the focal point of the current thesis, the pneumatic delivery and storage procedure in domestic storage facilities is briefly described in the following and illustrated exemplary by figure 2.3. For domestic delivery, wood pellets are usually loaded from storage silos at the plant into blowing trucks and subsequently transported to the customer. With conveying air, provided by the truck's compressor, the pellets are pneumatically blown via hoses through the house ports into the domestic storages. There, they hit an impact protection mat and accumulate at the bottom of the silo. Conveying conditions can widely vary depending on local circumstances or the vehicle-related parameters adjusted by the driver and thus result in different degradation effects, e.g. the hose length, mainly dependent on the distance between truck and house ports. Since the entire hose consists of individual pieces, the number of couplings increases with total hose length, which might have progressive influence on the entire degradation effect [c]. Further mechanical loads occur inside the buildings, e.g. number and geometry of pipe components (bends of different radii, pipe reducers, etc.). In addition to the conveying air, which can be split up inside the truck depending on the vehicle's design (e.g. into the silo cells or for subsequent acceleration) further parameters like pellet mass flow can be set by operating staff. Conclusively, this results in a wide range of possible flow conditions due to varying solids loading ratios. Since the conveying air flow is directly dependent on the hose length (or, in other words, on the pressure loss that needs to be compensated), the vehicle-related operating parameters often depend directly on local conditions.

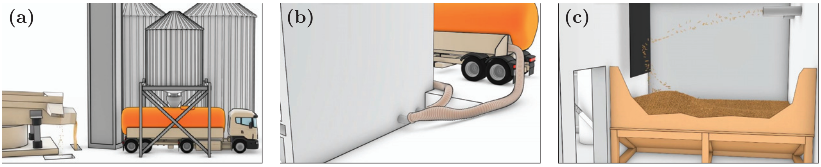

Figure 2.3: Steps of domestic pellet delivery: truck loading (a), pneumatic delivery from silo truck to house ports via hoses (b), silo loading (c) [60]

As an example of the size reduction effects of pneumatic deliveries on the pellets conveyed, figure 2.5 depicts the influence of hose length and conveying air flow on the resulting length distributions. For both hose length (a) and conveying air flow (b) the size reduction effects are clearly indicated by the respective length distribution curves being shifted to the left to shorter pellet lengths and the reduced average particle lengths.

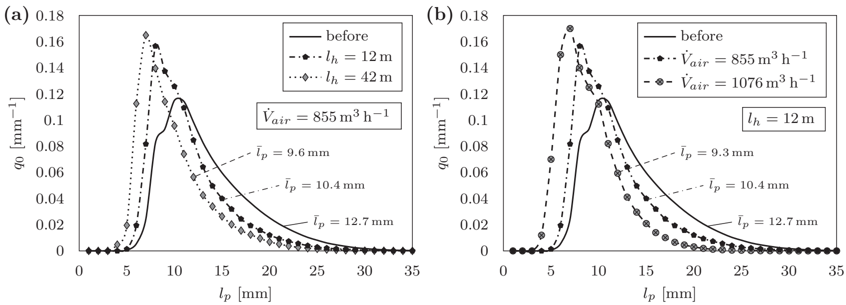

Figure 2.5: Influence of hose length (a) and air volume flow (b) on pellet length distribution during pneumatic delivery with a blowing truck [c]

2.1.3 Pellet degradation and fines formation

General tendencies of particle degradation and thus fines formation due to pneumatic conveying of bulk materials were comprehensively investigated (see section 2.3.4). Nevertheless, the results obtained can't be directly related to the pneumatic conveying of wood pellets [j]. For example, Mina-Boac et al. [153] and Aarseth [2] investigated the pneumatic transport of feed pellets. The authors determined a major effect of the conveying process, e.g. conveying velocities or number of transport repetitions and strong dependence of particle breakage on the durability of the pelletised particles. But the dimensions (3 to 6 mm diameter) and the mechanical durability (DU = 92 to 96 %) are considerably different from those of wood pellets (6 to 8 mm, DU = 98 to 99 %), so that the conclusions of both studies are not completely applicable to the degradation of wood pellets.

The number of both experimental and numerical studies on wood pellet breakage itself is comparatively low. For example, Oveisi et al. [167] investigated the comminution and abrasion effects of wood pellets by free-fall drop tests, taking into account different drop heights and repetitions. As expected, the study revealed that particle degradation increases with ascending drop heights. The durability of the pellets is reduced by repeating drop tests, thus the experienced loads are retained. Free-fall tests, however, represent the situation during pneumatic conveying only rudimentary.
Experiments on pneumatic conveying of wood pellets were performed by Abdulmumini et al. [3]. Their objective was to compare various types of strength testing devices and to determine whether the durability determined by these testers leads to the same trends in fines formation compared to an exemplary pneumatic conveying process. Thus, they were able to determine a general degradation effect of the conveying process, but did not specify the particle comminution or the influence of operating conditions in more detail.
Kotzur et al. [114] detected increasing wood pellet size reduction effects with rising pellet length and conveying velocity during lean phase pneumatic conveying. However, theses tests were limited on a sample size of only 100 particles. Again, the impact of pipe components and solids loading ratios on the particles' breakage characteristic was not investigated.
In a recent study, Wiese et al. [232] analysed pellet degradation and fines formation during pneumatic truck deliveries into a model storage. Here, hose length and impact protection mat position were varied. In addition, pellets of different origin were considered. Both longer hose lengths and shorter distances between impact protection mat and blowing connector increase the resulting fines content and thus confirm their influence on pellet size reduction during pneumatic deliveries. The pellet type of lower quality (and durability) leads to higher formation of fines.
In their tests with delivery trucks, Jägers et al. [c] confirmed the progressive influence of hose length and impact mat position on pellet breakage and fines formation. Further, they varied the pressure inside the truck's silo cells as well as the distribution scheme of the conveying air within the vehicle (ratio of driving air flow to acceleration air flow).