# Impact of Cooling Air Temperature and Airflow on Wood Fuel Pellet Durability, Hardness, and Off-Gassing During Industrial Storage

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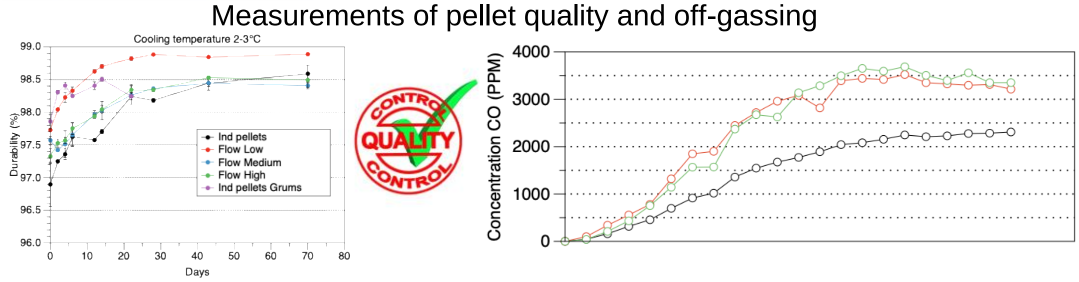
## GRAPHICAL ABSTRACT

Industrial cooling and storage of wood fuel pellets

Measurements of pellet quality and off-gassing



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The cooling of pellets is necessary because pellets reach 70 to 90 °C after the pellet press. The reduction in temperature solidifies the pellets, which increases the pellet quality and reduces the risk of self-heating during storage. Industrially, pellet plants use outdoor air in counterflow coolers and cooling ends when the pellet temperature is approximately 5 °C above ambient temperature. Cooling performed in the summer could result in high temperatures in the pellet stacks during storage, and cooling at low temperatures and high airflows in the winter could cause quality problems. Therefore, the aim was to determine how cooling air temperature, airflow, and storage time impact the durability, hardness, and off-gassing of the pellets. The results showed that the highest durability (97.7%) and hardness (310 N) were achieved when cooling with low-temperature air and low airflow. Additionally, durability and hardness stabilized at high values (98.9% and 640 N) after 30 to 40 days of storage, regardless of the airflow and cooling air temperature used. Furthermore, it was found that high airflows reduce off-gassing regardless of the cooling air temperature. It is recommended that the industry reduce airflow during the winter and increase it during the summer to produce high-quality pellets and minimize the risk of self-heating.

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*Keywords: Industrial cooling; Wood pellets; Airflow; Durability; Storage; Air temperature; Off-gassing*

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## INTRODUCTION

In 2023, global installed biomass pellet capacity exceeded 76 million metric tons (Sherrard 2024). This increase was driven by rising exports, fueled by the European energy crisis resulting from the conflict in Ukraine and the disruption of gas supply from Russia. The growing adoption of wood fuel pellets places additional demands on the industry, affecting not only production processes (such as grinding, conditioning, densification, and cooling) but also pellet quality and storage conditions.

Extensive research has been conducted on various quality parameters related to wood fuel pellets, including those derived from agricultural waste and feed. Commonly studied parameters include pellet durability, hardness, bulk and particle density, moisture content, and ash levels. Additionally, numerous studies have focused on binding agents to enhance pellet quality and reduce energy requirements during production (Fredriksson *et al*. 1998; Mani *et al*. 2006; Nielsen *et al*. 2009; Kuokkanen *et al*. 2011; Stelte *et al*. 2012; Berghel *et al*. 2013; Tarasov *et al*. 2013; Larsson *et al*. 2015; Anukam *et al*. 2019).

However, only a few studies have investigated the cooling process and its impact on pellet quality. Even fewer studies have explored its effects on pellet storage, particularly concerning off-gassing from stored pellets, especially in industrial scale.

The cooling of pellets is typically performed using belt coolers and counterflow coolers in industrial settings (Maier and Bakker-Arkema 1992; Ziggers 2004) , whereas the food industry commonly employs vacuum bed coolers (Zheng and Sun 2004). Forced convection in industrial coolers, as opposed to natural convection in ambient air, significantly reduces cooling time by several minutes or even hours and ensures more uniform cooling within the pellet bed (Akhmedov *et al.* 1980). These industrial coolers utilize electricity to power fans that distribute ambient air through the warm pellet bed, usually in a counterflow manner. Besides lowering the temperature and thus the latent heat of the pellets, the cooling process also decreases the moisture content by up to 1 to 2 wt% (Kirsten *et al*. 2016). The reduction in both moisture content and latent heat of the pellets depends on factors such as airflow and air properties, raw material characteristics, pellet size, and the height of the pellet bed in the cooler (Maier and Bakker-Arkema 1992; Thomas *et al*. 1997).

Newly produced pellets must be cooled from approximately 70–90 °C to 5 degrees above ambient temperature (Whittaker and Shield 2017) to resolidify or crystallize the binding agents or additives used (Thomas *et al.* 1997). Alakangas (2001) states that cooling stabilizes the pellets and hardens the lignin melt on the surface of pellets, and hence, the shape of pellets remains unchanged. During the cooling process, water evaporates, transforming wet bonds into dry, solid bonds and bridges (Thomas *et al.* 1997; Pileggi *et al*. 2001). Efficient cooling is essential; otherwise, temperature gradients between the inner and outer layers of the pellets can cause cracks, leading to more fines and an increased risk of breakage (Whittaker and Shield 2017). However, excessively rapid cooling at low air temperatures and high airflow can dry the pellet surface more than the interior, potentially causing additional cracks and making the pellets more susceptible to abrasion, resulting in more rejects during production (Thomas *et al.* 1997).

Additionally, cooling reduces the risk of condensation on the pellet surface, thereby preventing microbiological activity during storage (Whittaker and Shield 2017). The cooling process is also crucial for preventing self-heating during storage. Siwale *et al*. (2022) studied temperature rises in pellet piles during large-scale production and found that concentrations of carbon monoxide, carbon dioxide, and methane increased with storage time. The formation of these gases depended on the type of extractives present in the raw material, *e.g.* resin acids in pine, rather than the total extractive content (Siwale *et al*. 2022). Production managers at Swedish pellet plants report from their experience that increasing excess air at lower temperatures and extending cooling times reduce the risk of temperature rise in pellet piles during storage.

Proper cooling of pellets is crucial, as demonstrated by the research presented above. Therefore, the purpose of this work was to investigate how cooling parameters affect wood fuel pellet quality and storage properties. The aim was to determine how cooling air temperature, airflow, and pellet storage time impact the durability, hardness, and off-gassing of the pellets, and to determine whether there is a minimum storage time required to maximize pellet durability and hardness.

## EXPERIMENTAL

### Materials and Methods

The cooling tests were conducted at Swedish industrial pellet plants on relatively cold winter days. The outdoor temperature was 2 to 3°C on the test days, March 15, 2023, at Stora Enso's pellet plant in Grums, Sweden and March 16, 2023, at the Laxå Pellets plant in Laxå, Sweden. The raw material for pelleting in Laxå consisted of a mixture of fresh sawdust and stored sawdust (50:50 mix by weight), both from spruce and pine (50:50 mix by weight), producing 8 mm pellets. Laxå Pellets uses a high-temperature drum dryer before pelleting and a counterflow outdoor air cooler after pelleting. The industrial cooler has a capacity of 12 tons of pellets per hour, with a dwell time of 25 to 30 min in the cooler and an airflow of approximately 22,000 to 25,000 m³/h. In contrast to the raw material used in Laxå Pellet Plant, the raw material used in Grums was residue from their CLT (cross laminated timber) factory at the site.

The cooling of the pellets was conducted with increasing cooling airflows and temperatures. Two pellet samples were collected directly after the pellet press and scattered on a tarpaulin to cool slowly by natural convection inside the pellet plant at 18 to 19 °C. Two pellet samples were collected after the industrial cooler, using outdoor air (2 to 3 °C), in the subsequent shaker, at Laxå Pellets plant and at Grums Pellets plant. For the remaining tests, a custom-built cooling tower was used (Fig. 1).

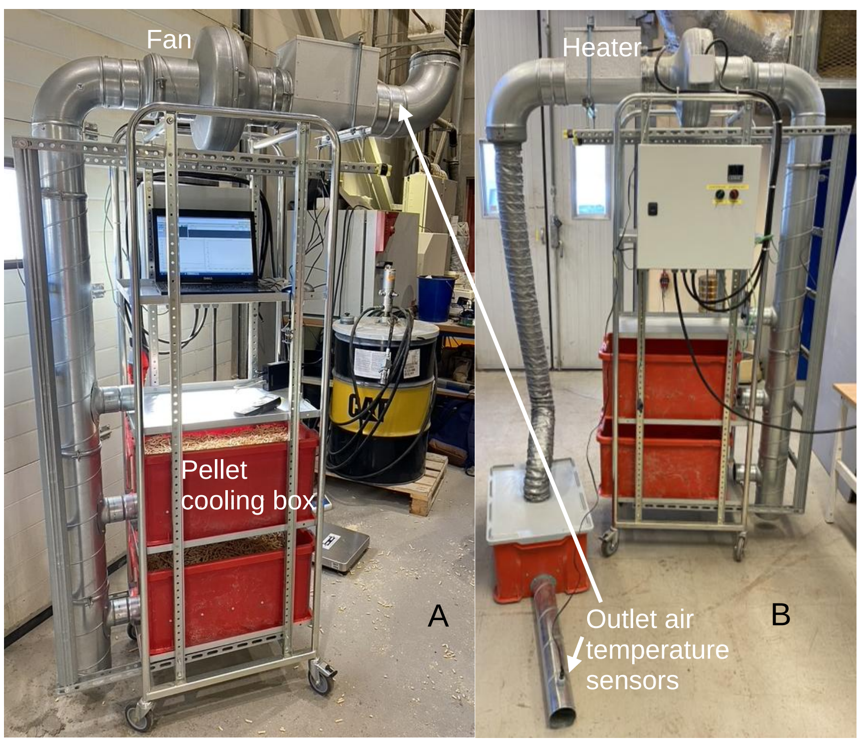


**Fig. 1.** The custom-built cooling tower used in the tests at the pellet industry, A) when cooled by indoor (18 to 19°C) and outdoor (2 to 3°C) air, and B) when cooled by preheated (35 °C) air

In the cooling tower, two pellet samples were cooled using outdoor air (2 to 3 °C, winter air), indoor air (18 to 19 °C), and preheated air (35 °C, summer air) at three different settings for the frequency converter for the fan (10, 30, and 50 Hz), corresponding to increasing cooling airflows (low 0.5 $m^3$/kg, medium 1.2 $m^3$/kg, and high 1.3 $m^3$/kg), as listed in Table 1. The fan (Type: CK 160 C, 90 W, 2450 rpm) was connected to the cooling boxes with ventilation pipes (diameter 80 mm), and air was drawn through the pellet boxes and expelled at the top of the cooler (Fig. 1A). When using 35 °C air, a heater (Type: CV 16-50-3M, 5 kW, IP 43) was employed, and the air was blown through the pellet bed and expelled through a pipe (diameter 80 mm, length 600 mm), as shown in Fig. 1B. The boxes could accommodate up to 25 kg of pellets (in the tests, the samples ranged between 16 to 22 kg each to ensure that enough tests could be conducted over 70 days of storage), and the boxes had a perforated sheet metal bottom where a temperature sensor was placed. When the sensor indicated a temperature 5±0.25 °C above the cooling air temperature (approximately 10 °C for the heated air due to the extended cooling time required), the measurement was stopped. Temperature were measured at the air outlet (see Fig. 1), and one sensor measured the ambient air temperature.

*Quality parameters analysis*

The quality parameters for the produced pellets in this test included moisture content (measured before and after cooling, and after storage), bulk density, durability, and hardness. Bulk density, durability, and hardness were assessed on the production day and periodically during storage, up to 70 days. Moisture content was determined according to ISO 18134-1 (SIS 2015). Bulk density was measured following ISO 17828 (SIS 2016). Durability was determined according to ISO 17831-1 (2015). Hardness was evaluated using a Kahl Hercules L pellet hardness tester, which applies radial pressure to the pellet until it breaks, with the applied force in kilograms recorded by the device. The load, denoted as N in the figures, was calculated by multiplying by the gravitational constant.

*Off-gassing measurements*

Off-gassing tests were conducted on Laxå Pellets using two samples from each of three different cooling methods: Air at 35 °C/Low Airflow, Air at 2 to 3 °C/High Airflow, and industrially cooled pellets. Off-gassing was measured every 24 hours for three weeks. Measurements included Oxygen ($O_2$), Carbon Monoxide (CO), Carbon Dioxide ($CO_2$), and Methane ($CH_4$). The pellets were stored in plastic containers with a total volume of 20 liters (Fig. 2).

**Fig. 2.** The containers and gas probe used for the off-gassing tests

The gas emissions and oxygen levels were measured using a multi-instrument based on electrochemical and infrared (IR) sensors (ECOM J2KN Pro-IN gas analyser, Palgo AB, Sweden) and calculated as described in (Siwale *et al.* 2022).

## RESULTS AND DISCUSSION

### Impacts of Cooling Conditions

Figure 3 illustrates the impact of high and low cooling air temperature and airflow on the cooling time and rate of cooling for pellets. The outlet air temperature represents the pellet temperature during cooling, as it is measured at the bottom of the custom-built cooler where the air exits. Higher airflows and lower cooling air temperatures resulted in faster cooling of the pellets (Fig. 3), which is advantageous for the throughput of pellets during industrial production. However, caution should be exercised, since Thomas *et al.* (1997) showed that rapid cooling at low air temperatures and high airflows could cause cracks in the pellets, which could result in more rejects during production. Previous research conducted at the pellet pilot plant at Karlstad University, using the same custom-built cooling unit (Fig. 1), demonstrated that the amount of rejects increased with higher airflows.

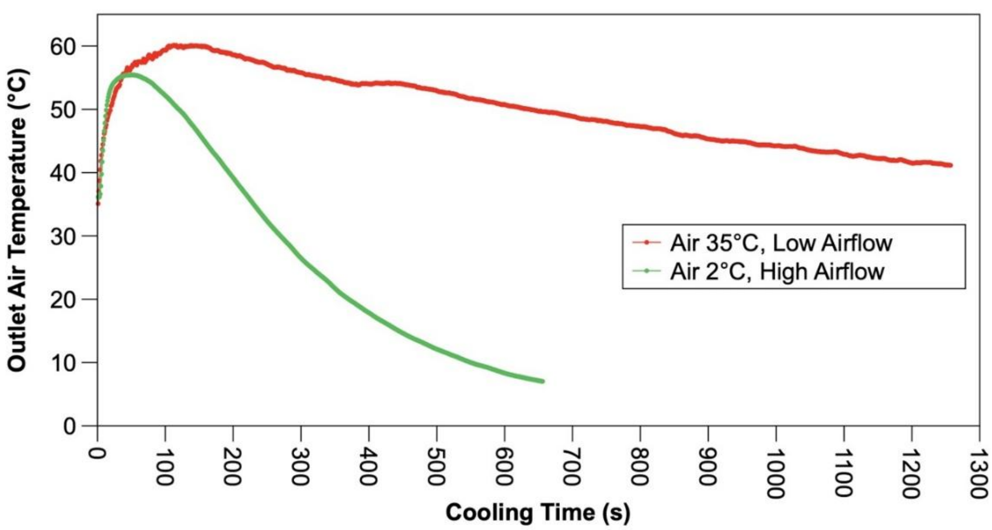


**Fig. 3.** The outlet air temperature vs. cooling time at high temperature and low airflow vs. low temperature and high airflow

In contrast, higher cooling air temperatures and lower airflows, *i.e.*, longer cooling times, resulted in increased drying of the pellets during the cooling process, as listed in Table 1. The moisture content decreased by an average of 1.2% during cooling across all pellet samples, in accordance with Kirsten *et al.* (2016). Maximum moisture loss occurred at a cooling air temperature of 35 °C with high airflow, indicating increased air passage through the pellets. This can be attributed to heat diffusing approximately 100 times faster than water (Bouvier and Campanella 2014), requiring more time for water to reach the pellet surface and evaporate. Additionally, high cooling air temperatures quickly reduce the temperature gradient between the pellet surface and the cooling air, decreasing mass removal. The mass concentration difference between the pellet surface and the cooling air is also greater at 35 °C compared to 2-3 °C.

**Table 1.** Moisture Content (wb) of Test Samples from Laxå Pellet Plant – Hot and Cooled Pellets, and Cooling Temperature and Airflow

| Samples | Hot Pellets MC (%) | Cooled Pellets MC (%) | Decrease in MC (%) During Cooling | Cooling Temperature (°C) | Airflow ($m^3$/kg of pellets) |
|---|---|---|---|---|---|
| Air 35 °C, Low Airflow | 8.4 | 6.3 | 2.1 | 35 | 0.5 ±0.1 |
| Air 35 °C, Medium Airflow | 7.5 | 6.5 | 0.9 | 35 | 1.2±0.1 |
| Air 35 °C, High Airflow | 7.6 | 4.8 | 2.8 | 35 | 1.3±0.1 |
| Air 18 °C, Low Airflow | 5.0 | 3.9 | 1.1 | 18–19 | 0.5±0.1 |
| Air 18 °C, Medium Airflow | 3.1* | 2.3 | 0.8 | 18–19 | 1.2±0.1 |
| Air 18 °C, High Airflow | 3.7* | 2.5 | 1.2 | 18–19 | 1.3±0.1 |
| Air 2 °C, Low Airflow | 7.2 | 5.4 | 1.7 | 2–3 | 0.5±0.1 |
| Air 2 °C, Medium Airflow | 6.4 | 5.4 | 1.0 | 2–3 | 1.2±0.1 |
| Air 2 °C, High Airflow | 8.7 | 8.1 | 0.6 | 2–3 | 1.3±0.1 |
| Air 18 °C, Natural Convection | 6.4 | 6.4 | 0.0 | 18–19 | 0 |
| Air 2°C, Industrially Cooled | 7.6 | 7.2 | 0.4 | 2–3 | 2.0 |

* A smoke detector halted production for several hours, impacting the moisture content of the samples used for indoor testing. The 18 °C samples have therefore been excluded.

## Bulk Density, Durability, and Hardness

The change in bulk density after 30 days of storage is presented in Table 2. The pellets produced in Laxå had a bulk density between 682 and 706 kg/m³ on the production day, which decreased by 2.4 to 4.4% after storage. The impact of moisture content on the change in bulk density was investigated, but all Laxå pellets still showed a decrease in bulk density at the same magnitude during storage. Over time, the pellets expanded in volume due to loss of structure integrity leading to a decrease in bulk density. This phenomenon did not appear to affect pellets produced from CLT residues in Grums, which only decreased by an average of 1.8 kg/m³, with some pellets even increasing in bulk density. The differences in results between Laxå and Grums pellets are further discussed below in the off-gassing section.

**Table 2.** Bulk Density (wb) of Test Samples from Laxå Pellet Plant – Fresh and Stored Pellets

| Samples | Fresh Pellets (kg/m³) | Stored Pellets (kg/m³) | Decrease During Storage (%) |
|---|---|---|---|
| Air 35 °C, Low Airflow | 682±5 | 657±3 | 3.7 |
| Air 35 °C, Medium Airflow | 687±4 | 657±14 | 4.4 |
| Air 35 °C, High Airflow | 686±8 | 666±10 | 2.9 |
| Air 18 °C, Low Airflow | 696±2 | 673±1 | 3.3 |
| Air 18 °C, Medium Airflow | 704±3 | 680±2 | 3.4 |
| Air 18 °C, High Airflow | 704±1 | 681±2 | 3.3 |
| Air 2 °C, Low Airflow | 706±8 | 688±2 | 2.5 |
| Air 2 °C, Medium Airflow | 692±15 | 669±10 | 3.3 |
| Air 2 °C, High Airflow | 696±11 | 679±0 | 2.4 |
| Air 18 °C, Natural Convection | 695±1 | 675±4 | 2.9 |
| Air 2 °C, Industrially Cooled | 688±2 | 663±4 | 3.6 |

The pellets were stored for up to 70 days, during which both their durability and hardness increased, as illustrated in Figs. 4 through 7. For reference, the figures also include data on natural convection-cooled pellets and pellets produced from CLT residual products. The durability and hardness stabilizes on high values after approximately 30 to 40 days of storage, regardless of the cooling air temperature or airflow used, as shown in Figs. 4 through 7. The time required to reach stabilized durability and hardness for pellets may be related to the decrease in oxygen levels during the first 20 to 30 days of storage, and the concurrent increase in carbon monoxide, shown in Fig. 8. Figures 4 and 6 show that pellets produced from CLT residues at the Grums pellet plant stabilizes at high values on durability and hardness after approximately 5 to 10 days of storage. This is believed to occur because the material is dried down to 2–3% (wb) before entering the CLT factory and thus the reactivity of the material has decreased.

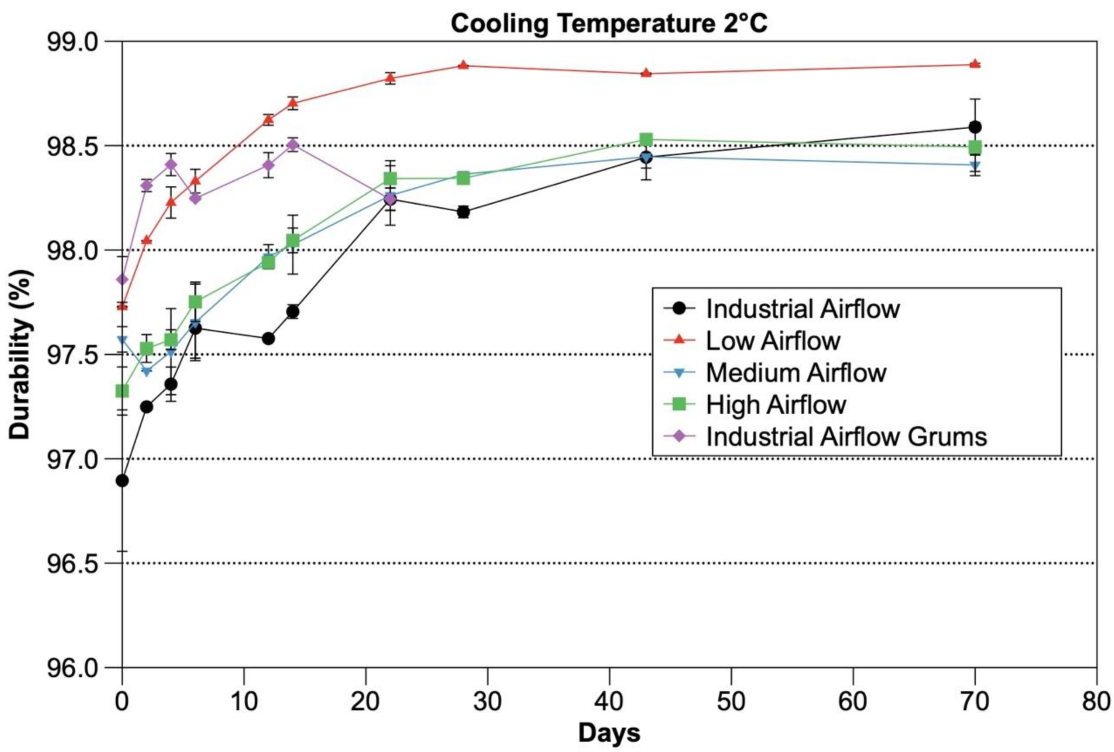


**Fig. 4.** The pellet durability, including standard deviation, vs. storage time for pellets cooled at low air temperatures

Figure 4 shows the change in durability during storage at a low cooling air temperature (2 to 3 °C), while Fig. 5 illustrates the change at a high cooling air temperature (35 °C). At low air cooling temperatures, a lower airflow resulted in higher durability. This could be attributed to findings by Thomas *et al.* (1997), which indicated that rapid cooling at low air temperatures and high airflows can cause cracks in the pellets, leading to more rejects during production and decreased durability. Rapid cooling may result in the pellet surface cooling quickly while the interior remains warm, creating a significant temperature gradient between the inner and outer layers, thus causing cracks. Additionally, the pellet industry could save electricity by reducing the power of cooling fans in winter when cooling at low air temperatures, as durability actually increases at lower fan speeds (Fig. 4), or increase the production rate of pellets while keeping the fan speed. Additionally, Fig. 5 shows that the durability of pellets was independent of the airflow used when cooling with warm air. The cooler's capacity decreased significantly (Fig. 3), and the time required to reach +7 °C above ambient temperature increased. Comparing Figs. 4 and 5, the durability after 30 to 40 days of storage was approximately 0.5% lower when cooled with warm air compared to cold air.

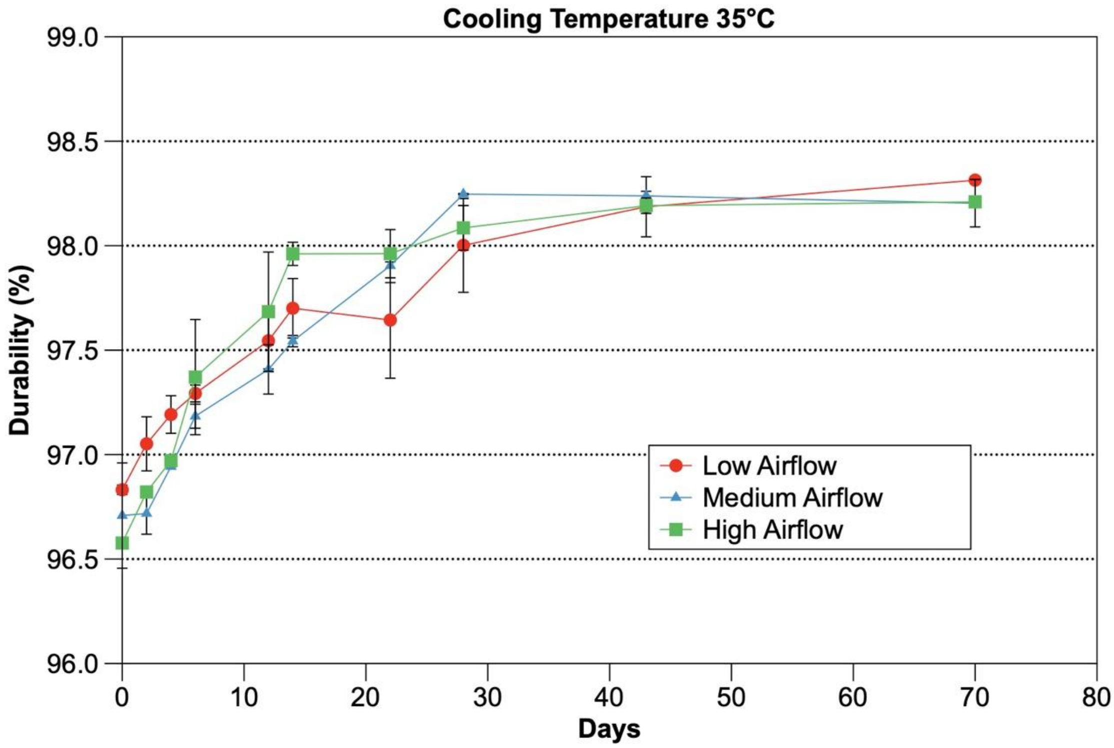


**Fig. 5.** The pellet durability, including standard deviation, vs. storage time for pellets cooled at high air temperatures

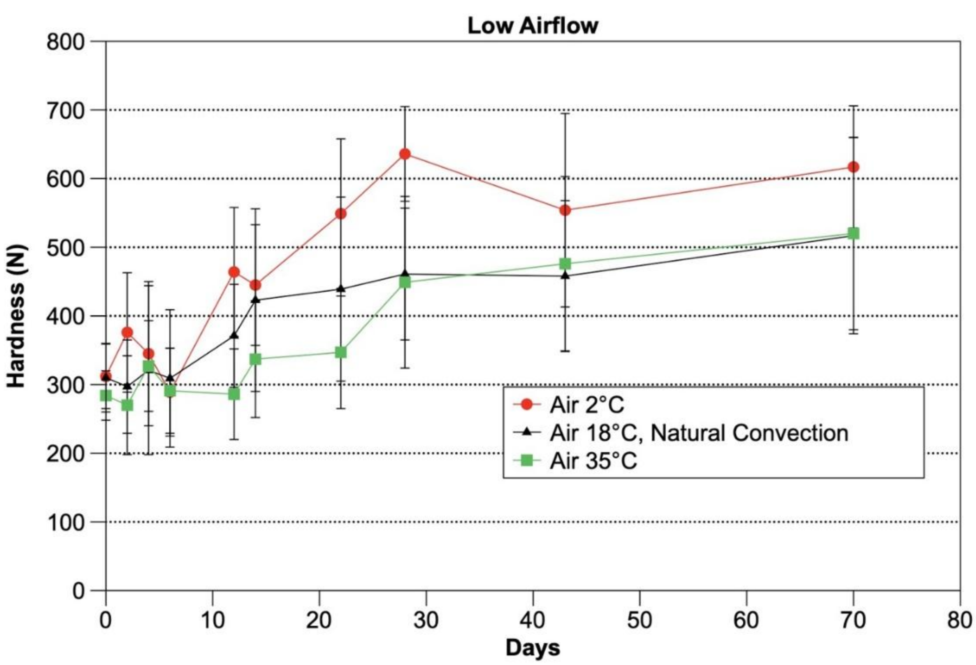


**Fig. 6.** The pellet hardness, including standard deviation, vs. storage time for pellets cooled at low airflows

Figure 6 shows the change in hardness at low cooling airflows, while Fig. 7 illustrates the change at high cooling airflows. For reference, Fig. 6 includes data on natural convection-cooled pellets, and Fig. 7 shows results for industrial cooled pellets from Laxå and Grums. Regardless of whether low or high airflows were used, a low cooling air temperature resulted in higher hardness, as illustrated in Figs. 6 and 7. Comparing Figs. 6 and 7, it can be observed that lower airflows may slow down the cooling process, allowing more time for the pellets to solidify and harden, as the hardness value was higher in Fig. 6 compared to Fig. 7. During storage the hardness increased by 70 to 100% for all Laxå pellets. However, pellets produced from CLT residues stood out as they exhibited lower hardness and matured earlier, as discussed above.

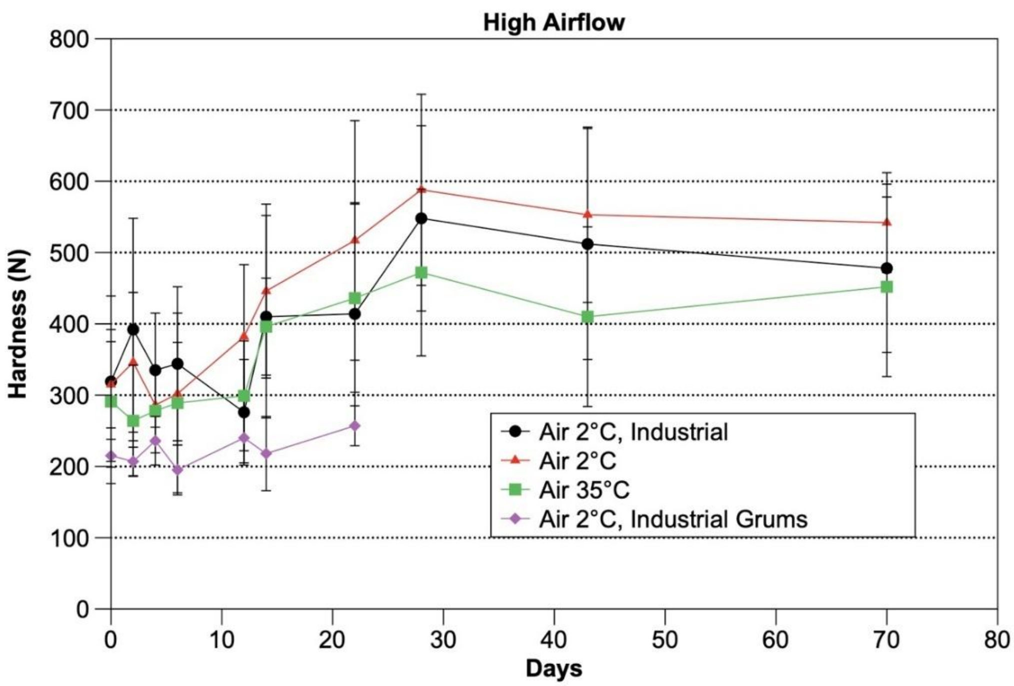


**Fig. 7.** The pellet hardness, including standard deviation, vs. storage time for pellets cooled at high airflows

## Off-gassing During Pellet Storage

In industrial settings in Laxå, the cooler is programmed to release the pellets when they reach 7 °C above the cooling ambient air temperature, regardless of the ambient temperature variations throughout the year. This will affect the pellet storage, especially when reactive raw materials, such as pine, is used, since the pellet temperature in the stack could initially be over 30 °C in summertime, which will increase the off-gassing and risk for self-heating (Siwale *et al*. 2024). High initial storage temperatures can pose a risk, as Guo *et al*. (2013) reported a temperature increase inside a wood pellet silo from 20 to 57 °C in 10 days, potentially leading to a fire. The pellet industry is well aware of the issues associated with reactive raw materials, such as fresh pine, and the potential for temperature rises in large pellet stacks. They have learned through experience, including incidents of pellet silos burning down, that excessive airflow over the pellets reduces the risk of self-heating. Table 1 presents the differences in airflow through the pellet cooler, showing that industrial coolers have an airflow of approximately 2 m³/kg of pellets.

Figure 8 presents the gas concentrations in ppm for CO, $CO_2$, and $CH_4$ and % (v/v) for $O_2$ over a 21-day storage period.

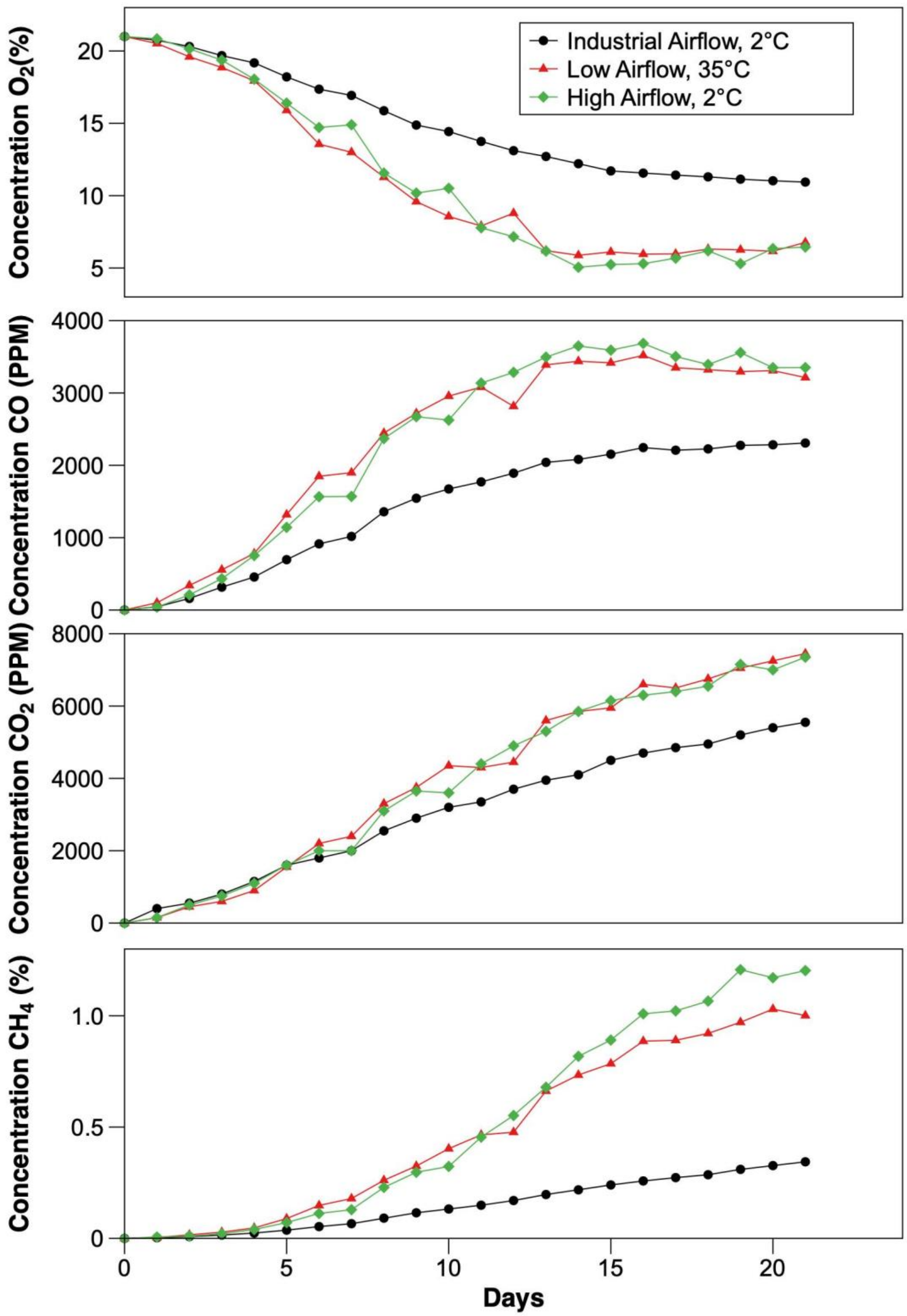


**Fig. 8.** The concentration of $O_2$ and CO vs. storage time for pellets cooled industrially, in low airflow at high temperature and at high airflow and low temperature

The $O_2$ level decreased from 21% and stabilized at around 6% after approximately 15 days of storage, except for the industrially cooled pellets, which decreased their $O_2$ content at a slower rate and stabilized at 11% afer 20 days. The CO concentration correlated with the $O_2$ concentration, as shown in Fig. 8; the more the $O_2$ concentration decreased, the more CO was produced during storage. Therefore, as the $O_2$ concentration decreased more slowly for industrial pellets, the production of CO was reduced. One possibility is that the formation of this toxic gas is a stress reaction of the wood cells (Siwale *et al*. 2024). Granstrom (2010) showed that pellets were low emitters of terpenes and hexanal after 40 to 50 days, indicating that the pellets are matured and the oxidation processes have stopped after about a month of storage. These findings could explain why the increase in durability and hardness leveled off after 30 to 40 days of storage. Because the oxidation processes had stopped, the risk of self-heating was close to zero. However, CO emissions increased during storage as oxygen levels decreased, which could be fatal when entering a pellet storage area. The World Health Organization (WHO) recommended limits are 10 ppm of CO for no more than 8 hours, and 35 ppm for no more than 1 hour (WHO 2010). The excessive airflow used industrially results in lower CO levels (Fig. 8), which might save lives even though durability decreases (Fig. 4). In this case, human lives could outweigh electricity savings and higher durability. Additionally, the gas concentration of $CH_4$ starts to increase after the stabilization of $O_2$.

## CONCLUSIONS

1. For Laxå pellets, the minimum time required to achieve stabilized high values of durability and hardness were 30 to 40 days of storage, independent of airflow and cooling air temperature during production. This implies that the pellet plant could aim to produce pellets with a standard durability value of over 97.5%, as durability is expected to increase by approximately 1% during storage.
2. High airflows reduced CO off-gassing regardless of the cooling air temperature used, potentially saving lives by protecting personnel entering storage buildings. The pellet industry uses excessive airflow in coolers to reduce the risk of off-gassing and self-heating, especially during summer conditions, which results in a slight decrease in pellet durability and hardness.
3. A recommendation for the pellet industry is to reduce airflow during winter when air temperatures fall below 0 °C. This approach can save on electricity costs and improve pellet durability and hardness by preventing cracks in the pellet surface.
4. Further industrial tests should include measuring the industrial cooler electricity use, the bed height of the pellets in the cooler, and the amount of fines/rejects after the cooler. By doing this, it would be possible to compare the savings on electricity costs to the changes in quality—such as durability, hardness, and the amount of rejects —as well as determining an optimal production rate.

## ACKNOWLEDGMENTS

The authors would like to express their gratitude to the pellet industries that participated in this study. All industrial tests were conducted at Laxå Pellets AB in Laxå, Sweden, with one test at Stora Enso Pellets in Grums, Sweden. The authors extend their thanks to the operating staff for their invaluable assistance and to the plant managers for permitting the cooling tests to be conducted in their operational pelleting plants. Thanks to Petrus Larsson for conducting several tests on pellet quality as part of his bachelor thesis.

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