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Reducing Product Loss Through Ventilation in Bourbon Maturation Warehouses

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Abstract: The aging process of bourbon within rickhouses is influenced by various environmental factors, including temperature, humidity, air flow, and air quality. Most rickhouses are not climate-controlled, and natural ventilation is a major contributor to airflow. The corrosion of the steel hoops on bourbon barrels occurs due to the presence of ethyl alcohol vapors and has become an issue for the distilling industry. The loss of a barrel or product is the loss of all of the energy and materials that went into the distillation, as well as the removal of the barrel from the secondary market. Despite the large economic and sustainability impact of barrel losses, there is limited published research with respect to corrective actions. This paper investigates airflow patterns within a bourbon rickhouse using a combination of differential pressure surveys and smoke tracing techniques to understand how natural ventilation impacts the aging process and potential for corrosion. A newly constructed rickhouse was surveyed using a micro-manometer to measure differential pressure and a sheet laser with smoke to visualize airflow. This study revealed significant zones of stagnant air and minimal recirculation within the ricks, which are the structures that hold the bourbon barrels. Airflow was found to primarily enter through windows and ground vents, moving along the walkways before exiting through other openings, with minimal penetration into the ricks. Differential pressure measurements generally indicated a lack of significant airflow, while smoke tracing showed that air entering the side of the building does not circulate into the ricks. This lack of airflow promotes the separation of ethyl alcohol vapor due to density, leading to its accumulation on the floor of the ricks. The findings of this study highlight the need to consider how rickhouse design impacts airflow and the potential for the corrosion of metal hoops on barrels due to the presence of ethyl alcohol vapor, and provide insight into optimizing the ventilation of rickhouses for more efficient and sustainable bourbon maturation.

Keywords: ethyl alcohol; natural ventilation; vapor pressure; rickhouse; smoke tracing

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1. Introduction

Warehouses designed for the maturation of bourbon are referred to as rickhouses, where the structure for storing the bourbon barrel holds the barrel horizontally. The storage structure is referred to as a rick in this paper. Rickhouses are primarily made from wood with metal siding and are typically five to seven stories tall. The design and total size of the rickhouse, along with the construction material, can significantly change the environmental conditions during the aging process. Environmental factors such as temperature, humidity, and air quality inside the rickhouse can significantly impact the aging process [1]. The majority of the rickhouses are not climate-controlled and rely on natural ventilation. In traditional designs, windows are used to control the airflow and temperature changes in the building.

The humidity surrounding the bourbon barrels affects the evaporation rate of water and ethyl alcohol out of the barrel. Higher humidities result in more ethyl alcohol than water being released, directly lowering the strength of the spirit. At lower humidity levels, the inverse is true, with more water than ethyl alcohol being released, thus increasing the strength of the spirit [2]. Evaporated ethyl alcohol poses an additional problem beyond the quality of the product; it causes the corrosion and degradation of the metal hoops that hold the bourbon barrel together. Barrels expanding during increased temperatures will apply more outward pressure on the hoops, and hoops that have been heavily corroded will often fail. This corrosion occurs more frequently to barrels on the lower floors of the rickhouse due to ethyl alcohol vapor's density, which is higher than that of air.

Understanding airflow patterns within a rickhouse plays a vital role in sustainability efforts by addressing the corrosive effects of ethanol vapor and optimizing the aging process. Corrosion poses a significant challenge, as it can weaken the metal hoops securing the barrels. If these hoops fail, the barrel may rupture, resulting in a loss of its contents and the resources used to create them. This includes the oak barrel, which cannot be reused after failure, the water used during fermentation, and the spirit itself, as well as the energy expended for fermentation and distillation. By mitigating corrosion, fewer barrels will fail, reducing waste and enhancing the overall sustainability of distilling operations. The authors have had multiple conversations with industry professionals who have highlighted barrel hoop corrosion as a result of humidity and ethanol concentrations. Additionally, multiple oral presentations have been given at the Jim Beam Institute conferences highlighting this issue. The Jim Beam Institute conferences are held at the University of Kentucky on an annual basis.

Many major distillers have identified waste and water usage as targets for their sustainability goals. For example, the Campari Group has a targeted zero waste to landfill goal by 2025 and aims to reduce water usage by 60% [3]. Suntory, another major company involved in distilling, has targeted a 50% reduction in water usage by 2030 and recognizes the importance of wood to their business [4]. Addressing corrosion within rickhouses aligns with these broader sustainability goals, providing an opportunity for the distilling industry to enhance efficiency, preserve valuable resources, and minimize its environmental impact.

Efforts to reduce barrel waste also align with several United Nations Sustainable Development Goals (SDGs), particularly Goal 9 (Industry, Innovation, and Infrastructure), Goal 11 (Sustainable Cities and Communities), and Goal 12 (Responsible Consumption and Production) [5]. Tackling barrel corrosion extends barrel lifespans, minimizing the need for replacements and conserving essential resources like oak, water, and energy. These measures align with Target 9.4's focus on sustainable infrastructure and Target 9.2's promotion of efficient industrialization.

Reducing waste contributes to environmental targets under Goal 11, such as Target 11.6, by lowering the industry's overall environmental footprint. While not directly tied to urban environments, the broader benefits of sustainable practices in distilling extend to global resource conservation. Additionally, efforts to enhance barrel durability support Target 11.c by promoting resilient and sustainable industrial practices, particularly in regions with developing industries.

Under Goal 12, minimizing barrel waste addresses Target 12.2 by ensuring the sustainable use of natural resources, including oak wood, and Target 12.5 by reducing waste generation through prevention and reuse. By addressing corrosion and reducing barrel waste, the distilling industry can conserve resources, reduce its environmental impact, and contribute to global sustainability goals, reinforcing its commitment to a more sustainable future.

Natural changes in temperature due to seasonal variation are a major driving factor in product taste and aging speed [6,7]. During warmer weather in summer, the barrels expand and allow the bourbon to enter the oak pores, while in the winter, the barrel contracts and expels the bourbon back out of the pores [8]. While in the pores of the oak, the bourbon absorbs additional flavors and, when expelled out of the pores, take the flavors with it. Barrels are made from wood, which is a natural product, and contain subject defects, allowing for liquid loss through holes or through pores. "This means the amount of liquid in a barrel will decrease over time, usually between 2–5% per year" [9].

In an alternate warehouse style for storing barrels called a Stackhouse or pallet house, barrels are stacked on pallets with the barrels themselves providing support. Failure of barrels on the bottom row can be catastrophic, leading to collapse. In rickhouses, barrels that fail will cause a cascade of failures because of the volume of alcohol released. Corrosion is not limited to barrels and can affect structural steel, conduit, and other corrodible materials. In an extreme example, extended ethyl alcohol accumulation can lead to it entering the explosive range. The airflow inside a rickhouse or pallet house is an act of balancing the natural temperature/humidity changes and restrictions to airflow. Understanding the airflow patterns within the rickhouse is essential so that current conditions can be understood and future changes to the airflow regime be better predicted.

2. Background

Research on interior ventilation and ventilation surveys have been performed on various types of storage facilities and warehouses. Research has been performed to characterize the ventilation and indoor air quality of food product storage facilities [10,11]. A key component of this work is measuring the airflow directions within the storage facilities, which provides valuable context for the analysis of indoor air quality and ventilation [10,11]. These storage facilities, like rickhouses, store consumable food products but differ in their temperature-controlled nature.

As highlighted by Brinks et al. (2015) [12], research and developed research methods for warehouse airtightness and air infiltration have fallen behind residential and office building research. There has been an effort to fill this gap through research on airflow into and out of warehouse buildings [12,13]. However, there is an apparent gap in current knowledge for the airflow characteristics of the specialized rickhouses in the distilling industry, which prompted the following work. A method of characterizing airflow into a warehouse's envelope is the measurement of differential pressure via a micro-manometer, which is utilized in this paper and in Iordache and Iordache (2017) [13].

Moreover, in this paper, sheet laser and smoke were used to characterize the airflow inside the rickhouse. This method has not commonly been used for this type of research; however, utilizing a sheet laser has been a common approach to visualize flow patterns in many different fields. One of the main benefits of this approach is its ability to provide a clear view of flow patterns within the illuminated area. Utilizing a sheet laser allows for the illumination of particles as they reflect the light from the laser [14]. For cases where the flow medium is not reflective, a tracer smoke gas can be utilized to provide reflection [15–18]. In special cases, other reflective particles can be utilized, such as dyes [19]. Smoke gas is one of the more easily applied tracers as it can conform to the surrounding airflow and provides indirect observation of flow materials like regular air. Sheet lasers have been used in many high airspeed applications [15,20]. Interior airflow often falls under low airspeed conditions. This level of speed has been visualized successfully by utilizing sheet lasers combined with smoke or a dye fluid [16]. A sheet laser and smoke can be used to trace airflow and provide effective real-time airflow visualization.

The initial motivation for this study was the industry-observed accelerated corrosion of bourbon barrels' galvanized steel hoops. The barrels are exposed to outside conditions via natural ventilation, allowing for interior humidity to rise and fall with ambient humidity. As outlined by Yadav et al., 2004, the corrosion of galvanized steel's zinc coating is accelerated when subjected to wet–dry cycles [21]. Natural temperature and humidity can cause regular condensation on the barrels; however, barrels have longer periods of condensation. Barrel temperatures stay closer to yearly averages than the instantaneous temperature, allowing for them to remain under the dew point for longer. This increased condensation contributes to the wet–dry cycle. Another factor is the presence of ethyl alcohol, either in liquid form due to leaks or in vapor form due to evaporation. The ethyl alcohol often mixes with the water condensate. Ethanolic solutions have been shown to decrease the open circuit potential values of steel, increasing the potential for corrosion [22]. A gap in current knowledge exists in the factors that drive ethanol accumulation within these rickhouses and is a motivation for investigation into such occurrences.

3. Materials and Methods

3.1. Case Study

A ventilation survey was performed at a Koetter Group property in Shelbyville, Kentucky, in a newly constructed, empty rickhouse. These warehouses were constructed using the recently introduced K-RAX system. This warehouse was capable of storing approximately 25,000 barrels in 3 stories of ricks. The footprint of the building was ~38 m (125 feet) × ~76 m (250 feet) and was ~9 m (30 feet) tall at the peak of the roof. The central walkway was open from the poured concrete floor to a cupola in the roof. Walkways surround the ricks to the outside wall on each level. Barrels will be loaded with a modified forklift and positioned from the walkways between the ricks. No effort was made to seal the building envelope in sheathing. A vent was built into the intersection of the floor and outside walls along the entire structure.

The objective of the ventilation survey was to determine the airflow patterns within the rickhouse. The ventilation survey was performed using a micro-manometer (DP-Calc™ Micromanometer model 5815 by TSI Shoreview, MN, USA), a smoke machine (Bullex SG4000 LION Group, Dayton, OH, USA), and a sheet laser (Z20M18B-F-532-lp45 Z-LAZER GmbH, Freiburg, Germany). The survey took place in the late afternoon and early evening. During the survey, the wind direction (outside of the building) was south-southwest. The temperature inside the building was 13.9 °C (57 °F) on the walls and 7.8 °C (46 °F) on the floor.

The novelty of this study is the investigation of airflow for a unique building type. This building type is unique due to (1) its unusually high number of windows, (2) the specialized storage system of ricks, (3) the prevalence of potentially corrosive ethyl alcohol from the stored product, and (4) the reliance on natural ventilation without air conditioning. This work was also able to capitalize on a unique opportunity. The rickhouse at the time was empty of product, enabling the use of laser smoke tracing for airflow. Within a filled or partially filled rickhouse, the smoke would have the potential to affect the taste and smell of the product.

3.2. Differential Pressure Surveys

Pressure measurements were taken in multiple locations throughout the rickhouse to gain quantitative data for internal airflow. A DP-Calc™ Micromanometer model 5815 with tubing was used to obtain the differential pressure between two locations. Detecting a differential pressure between two locations indicates air movement. The pressure differences detected by the manometer correspond to the drop in pressure due to friction. This frictional pressure drop corresponds directly to the airflow between the two points [23]. If there is no detected difference in pressure, there is no airflow between those two points.

According to the DP-Calc™ Micromanometer model 5815 specifications [24], it has a listed accuracy of ±1.244 Pa. Any measurement within the range of 0 ± 1.244 Pa was considered non-significant, and a difference in pressure of zero was recorded.

As shown below in Figure 1, the differential pressure between the exterior and interior of the warehouse was measured through the main rollup door (Point A) to determine if any airflow in or out of the rickhouse was present. Measurements were taken traversing down the main walkway of the rickhouse in between the two main ricks (Points B and F). Measurements were then taken traversing perpendicular to the main walkway from the side of the building and through the ricks (Points C, D, E, and G).

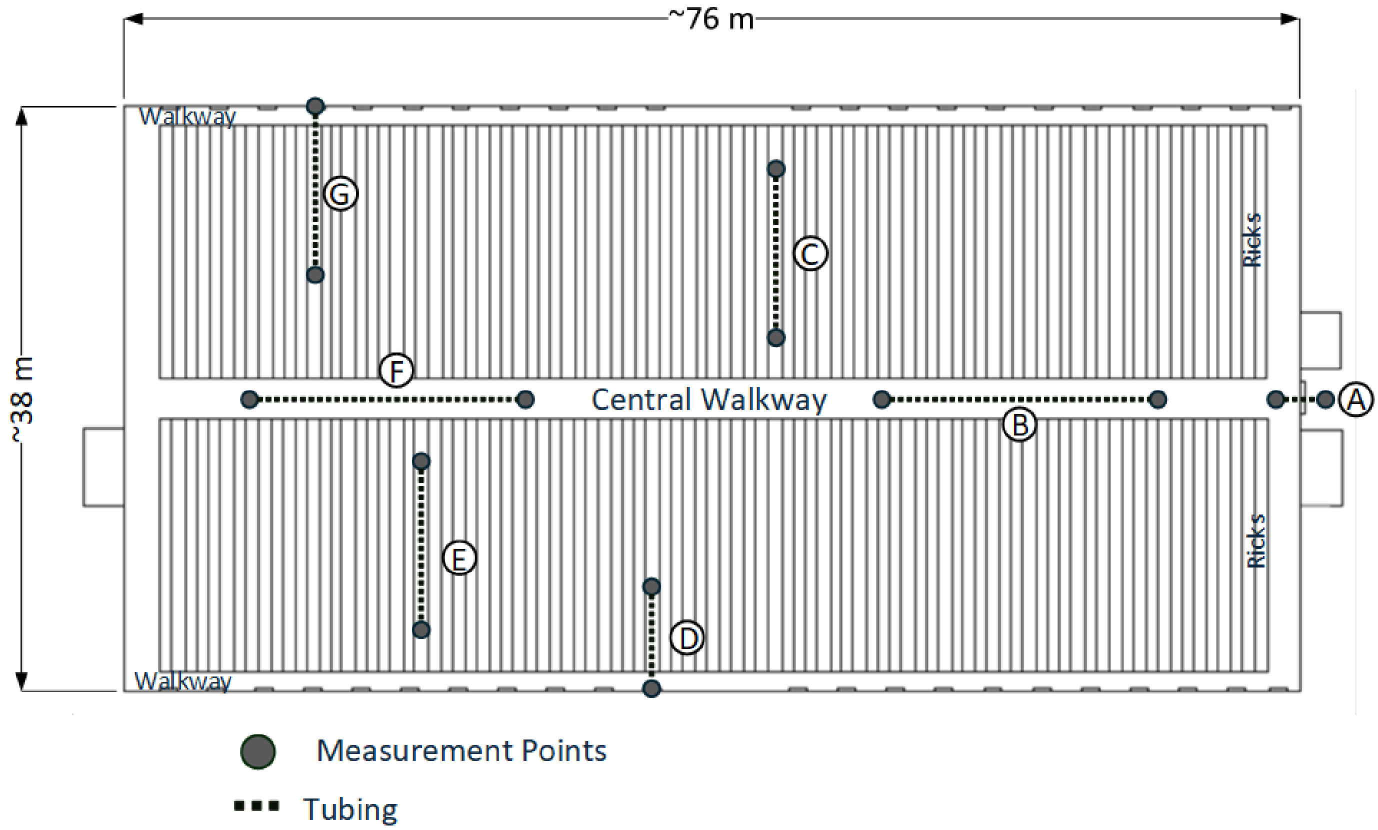

Figure 1. Differential Pressure Measurement Locations.

3.3. Smoke Surveys

The smoke survey was conducted to visualize airflow patterns within the rickhouse using a combination of a smoke machine and a sheet laser. The smoke machine (Bullex SG4000) generated smoke that acted as a tracer, moving with the surrounding air currents, while the sheet laser (Z20M18B-F-532-lp45) illuminated the smoke particles, making the airflow visible. This method allowed for the observation of real-time air movement within the rickhouse.

The sheet laser was positioned to bisect the smoke as it moved, oriented parallel to the direction of the smoke's movement to allow for a longer view of the smoke's path. This contrasts with a perpendicular orientation, which would only provide a brief view as the smoke passed through the laser. The smoke tests were recorded using video, allowing for later analysis and review. The videos captured the real-time air movement (or lack thereof) and were used to establish airflow patterns. Several images were then extracted from a number of video sequences that showcase air movement and were included in the results and discussion section of this study. When possible, a perpendicular view was also set up to capture the smoke tests to provide the best visual clarity. This experimental setup is shown in Figure 2.

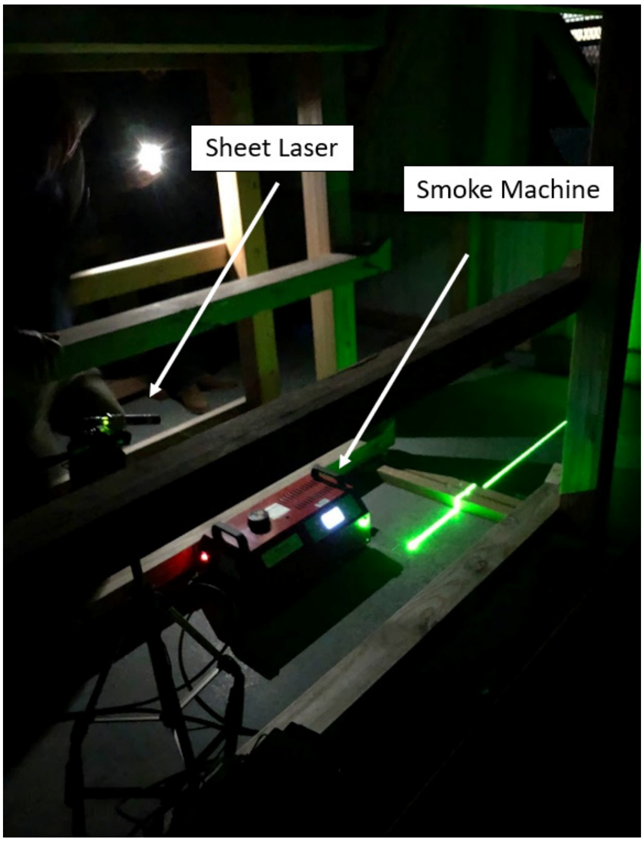

Figure 2. Smoke Tracing Experimental Setup.

It is important to note that the smoke exiting the machine had momentum as part of the machine's functionality. The smoke quickly loses this momentum after being emitted and conforms to the local airflow regime. As such, the first seconds of tracing are not accurate to the surrounding airflow. Additionally, if there is no airflow current for the smoke to adhere to, the smoke will rise due to its lower density and higher temperature. Multiple smoke tests were completed at various locations to characterize the airflow patterns within the rickhouse, as shown in Figure 3.

During an earlier visit, the authors sensed, but could not measure, air movement in the vicinity of the rollup door. To determine airflow in and out of the rickhouse, smoke was released near the main entrance roll up door. This was undertaken on either side of the entrance with the door open and closed.

To test the airflow through the windows and ground vents on the sides of the rickhouse, smoke was released from outside the rickhouse near the side walls. Smoke was released inside the ricks, traversing perpendicular to the main walkway. Finally, smoke tracing was performed on the third floor of the rickhouse.

The combination of smoke tracing and sheet laser visualization allowed for the identification of airflow paths, areas of recirculation, and zones of stagnant air within the rickhouse. The results from the smoke survey were then used to supplement the quantitative data obtained from the differential pressure measurements.

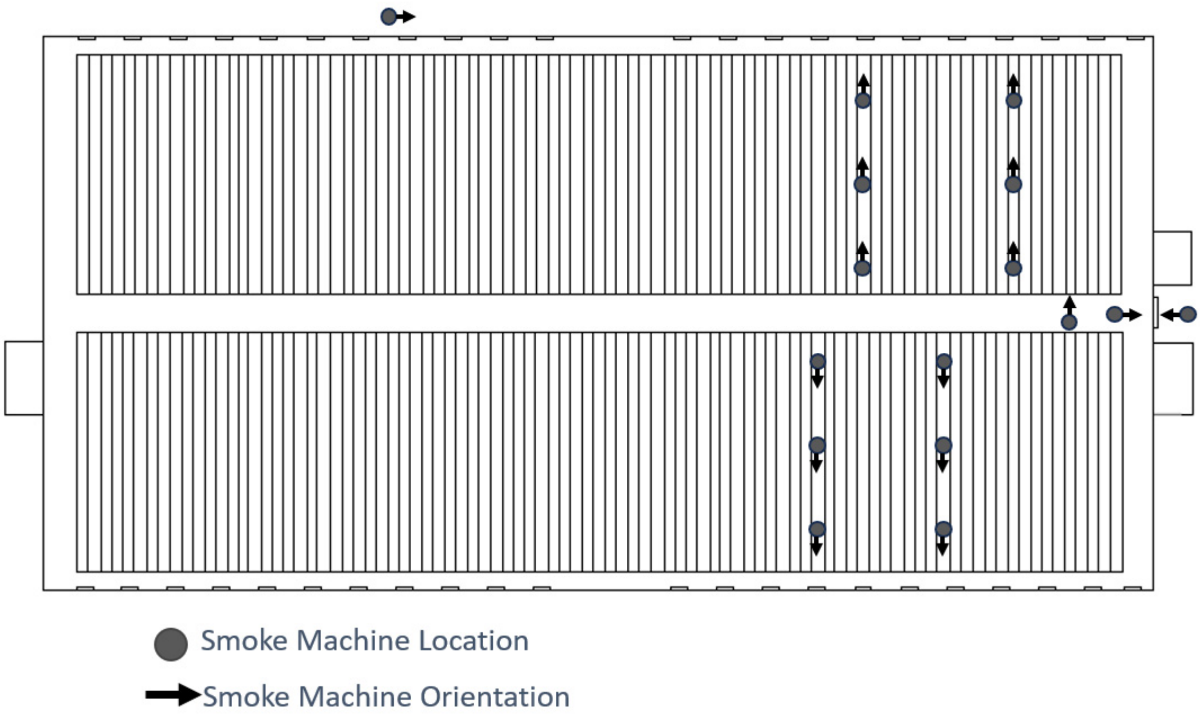

Figure 3. Smoke Tracing Locations.

4. Results and Discussion

The research team had only one opportunity to collect smoke measurements as these measurements needed to be taken at night due to the use of a laser, and at an empty rickhouse as smoke should not be introduced at an active storage facility. As such, no measurement statistics could be generated as multiple measurements could not be obtained. The objective of the differential pressure measurements was to determine whether there was any airflow, not to quantify the airflow (if any). The objective of the smoke surveys was to determine airflow patterns and confirm locations of stagnant air identified by zero differential pressure measurements. The first two subsections present the results for the different measurements and surveys, while the third subsection discusses the airflow patterns confirmed by the above-mentioned measurements and surveys.

4.1. Results for Differential Pressure Measurements

Table 1 shows the measured differential pressure from the survey; the test locations can be seen in Figure 1. At test location A, which measured the differential pressure through the main entrance, a differential pressure of 0.747 Pa was recorded. This measurement was within the margin of error for the micro-monometer and was considered a non-significant reading. Treating this reading as a 0 value indicates no airflow is coming in or out of the rickhouse via the main entrance. Test locations B and F measured the airflow down the main walkway. Again, the measurements were within the margin of error for the micro-manometer and considered 0 values. For measurements inside the ricks at locations C and G, the measurements were again in the range to be considered a 0 value. The only locations with notable differential pressure readings were locations D and G. These values were directly correlated to an uptick in wind and likely the source of the differential pressure. This shows that air enters naturally through the windows of the rickhouse.

Table 1. Differential Pressure Readings.

Test Location	Recorded Differential Pressure	Effective Differential Pressure
A	0.747 Pa	Zero
B	0.498 Pa	Zero
C	0.747 Pa	Zero
D	6.221 Pa	6.2 Pa
E	0.747 Pa	Zero
F	0.747 Pa	Zero
G	3.981 Pa	4.0 Pa

The differential pressure measurements taken inside the rickhouse were generally very low, often falling within the margin of error of the measuring instrument. Measurements at the main entrance, main walkway, and inside the ricks were all within this margin of error, effectively indicating no measurable airflow at these locations. Only locations correlated with an increase in wind speed outside the building showed notable differential pressure readings. This indicated that airflow within the rickhouse is very subtle and not easily measurable using a pressure-based method. These limitations of the differential pressure measurements led researchers to use smoke tracing to better understand airflow in the rickhouse.

4.2. Results for Smoke Surveys

The first set of smoke tests was performed to determine the airflow into the rickhouse through the main entrance. Figure 4 shows four frames from the recorded video. In frame 1, the initial velocity given to the smoke from the machine is shown. In frame 2, the smoke conforms to the ambient airflow and halts before entering the rickhouse. In frame 3, the smoke reverses and flows away from the entrance. Frame 4 shows the smoke completely flowing away from the entranceway. This experiment was repeated on either side of the entrance with the door open and closed. In all cases, no smoke migrated in or out of the rickhouse via the main entrance.

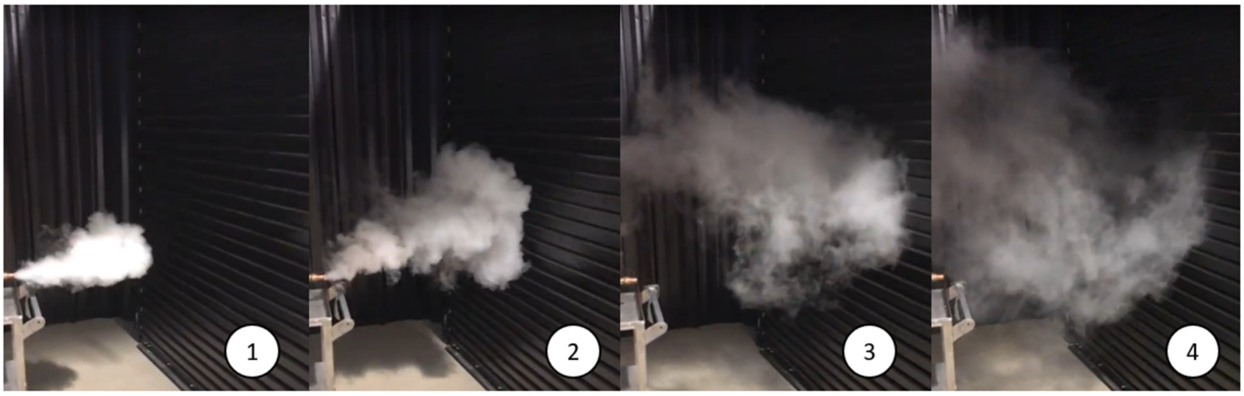

Figure 4. Main Entrance Smoke Test.

The next set of smoke tests were performed on the side walls of the rickhouse, which had windows and ground vents that could potentially allow for airflow in and out of the building. Figure 5 shows four frames from the recorded video for this test. Frame 1 shows the initial condition before smoke was emitted. In frame 2, the emitted smoke first enters the rickhouse via the nearby window. Frame 3 shows smoke rising from the ground, and in frame 4, the smoke begins dispersing down the hallway. Eventually, the smoke exited out of the rickhouse through another set of windows further down the hallway. While performing tests on the side walls of the rickhouse, the smoke entered regardless of the ambient wind direction. For the test shown in Figure 5, the wind direction was opposite to the direction of smoke flow into the rickhouse. This is likely due to a recirculation zone, as wind contacted the wall opposite the one shown in Figure 5. An area of low pressure was created, allowing for a recirculation zone to form and air to enter through the windows while the wind moved in the opposite direction. This is in line with the ASHRAE Handbook 1981 Edition, which provides centerline flow patterns around rectangular buildings [25]. Figure 6 displays a test with the sheet laser reoriented to be perpendicular to the hallway and shows that the smoke, when entering the rickhouse through the windows and ground vents air, does not migrate into the ricks. In the photo, smoke concentrates closer to the wall than to the rick on the right of the photo.

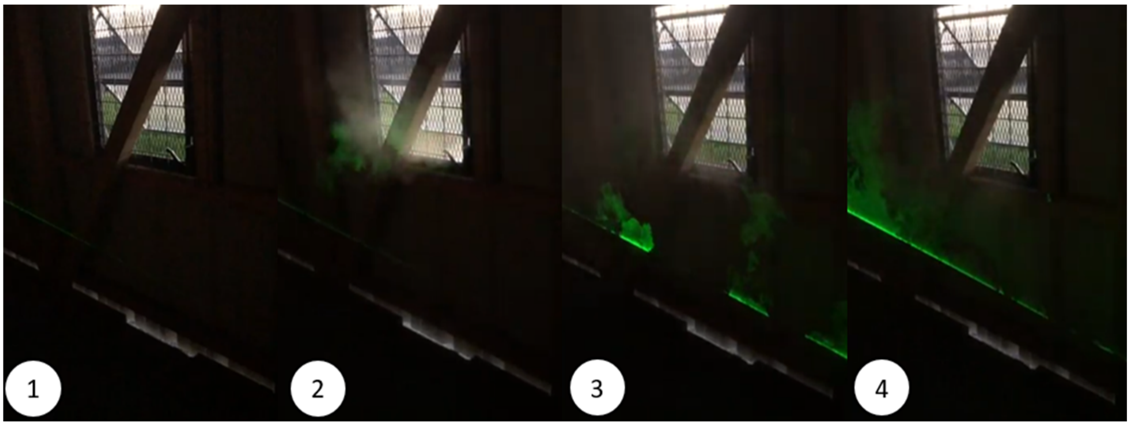

Figure 5. Windows and Ground Vent Smoke Test.

Figure 6. Perpendicular Angle for Windows and Ground Vent Smoke Test.

Several smoke tests were conducted within the ricks of the rickhouse. These ricks were empty at the time of the tests. Figure 7 shows three frames of a representative video for the tests performed within the ricks. Frame 1 shows the smoke as it is initially emitted. Shortly after, in frame 2, the smoke begins to lose its velocity and rise due to its higher temperature and lower density. Finally, in frame 3, the smoke loses its horizontal velocity and disperses upwards. This effect is shown again in Figure 8, which depicts frames from another smoke test performed inside the ricks. In frame 1 from Figure 8, smoke is shown lingering and recirculating from a previous test. New smoke is then emitted, loses velocity quickly, and begins recirculating. Twelve of these smoke tests were completed in various locations inside the ricks, and all had very similar results to Figures 7 and 8. This suggests that resistance to airflow is very high within the ricks. This is likely due to the structure of ricks, as supports and racks provide obstacles to free air movement. This also explains why air entering from the side windows and ground vents, as shown in Figure 6, does not easily enter into the ricks but rather flows back out through another set of windows and vents.

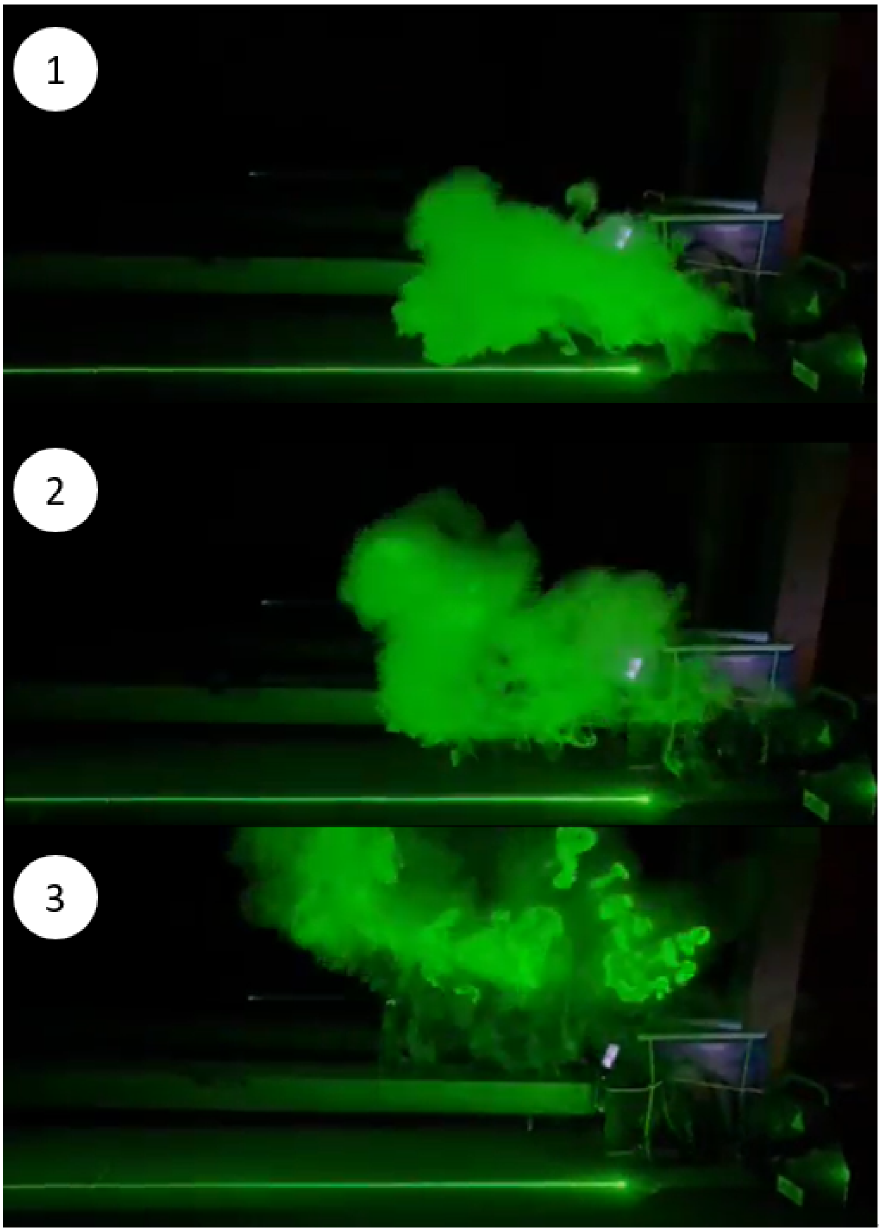

Figure 7. First Interior Rick Smoke Test.

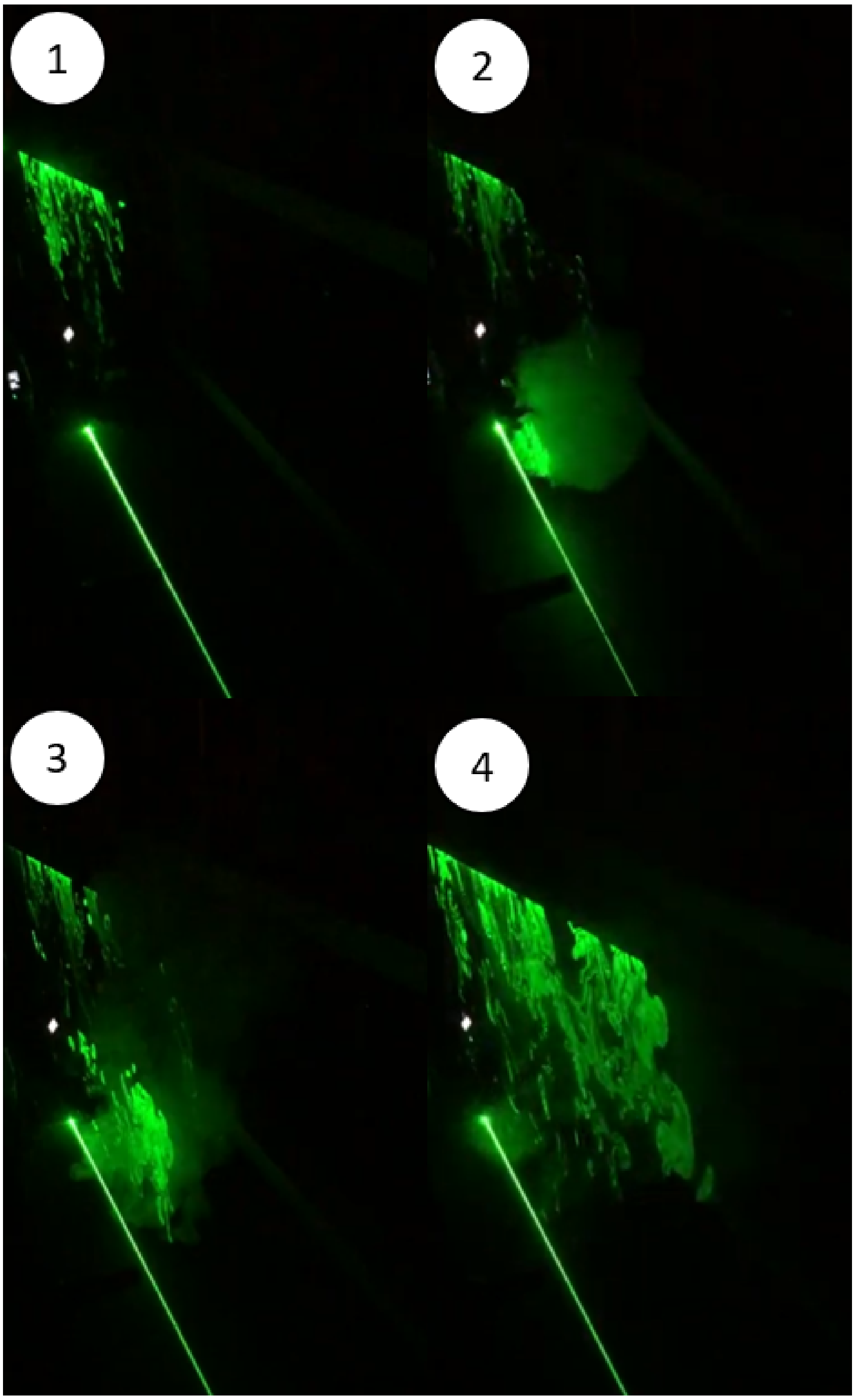

Figure 8. Second Interior Rick Smoke Test.

The final smoke tests were performed on the third floor of the rickhouse, with smoke being emitted into the center of the warehouse. Figure 9 shows four frames from the recorded video. Frame 1 shows the initial conditions where the smoke had previously been emitted but lingered and recirculated. In frame 2, the emitted smoke reaches the sheet laser. Smoke in frame 3 begins to disperse, and in frame 4, the smoke splits into two areas. In frame 4, smoke on the left of the frame begins to recirculate, and smoke on the right of the frame begins to exit the rickhouse through a nearby cupola above the central walkway.

The following section summarizes the findings of the smoke surveys as they pertain to airflow patterns.

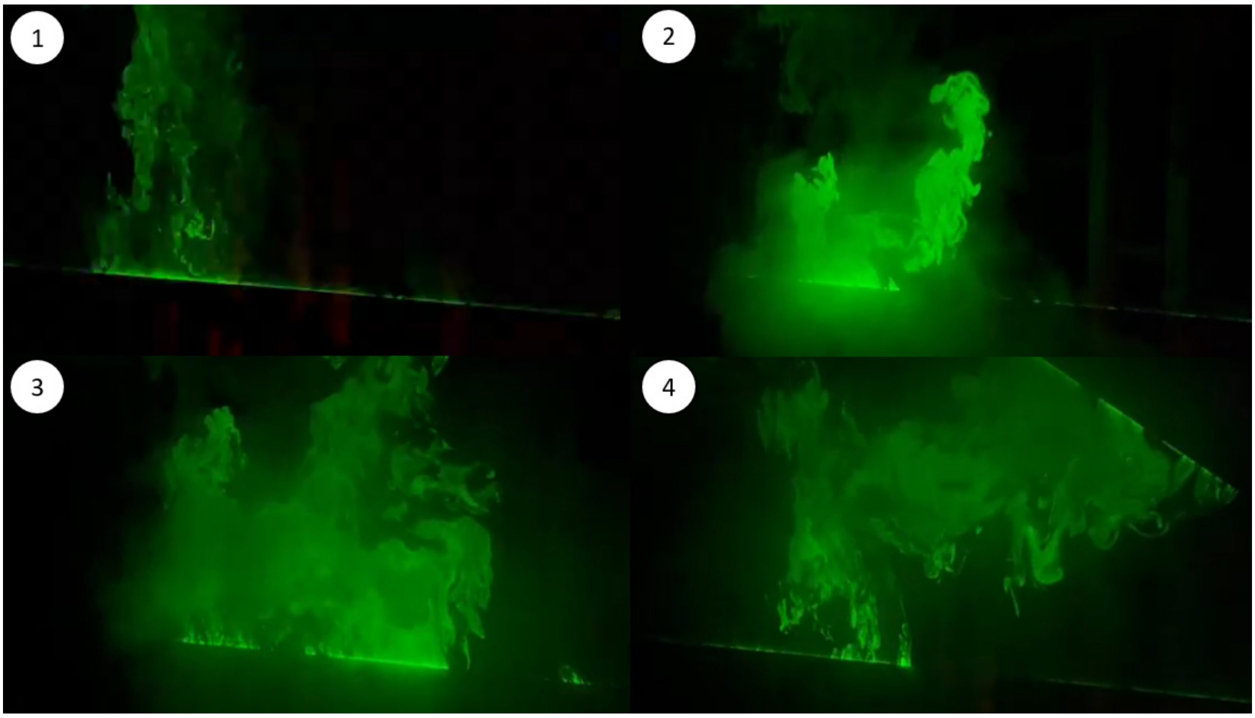

Figure 9. Third Level Smoke Test.

4.3. Discussion on General Airflow Patterns

Performing differential pressure tests and smoke tracing allowed for the general characterization of the rickhouse's airflow. Based on the smoke tests completed around the walls of the rickhouse, there air entered naturally through the windows and ground vents. As depicted in Figure 10, the air entering through the sides could not ingress further into the rickhouse due to the high resistance of the ricks. As a result, the air was forced down the walkway between the wall and ricks before exiting back out through another set of windows. Air flow is depicted with arrows going in and out of the section of the building (on the edges) by the respective symbols in Figure 10. Air entering through the top windows did not have this issue, as the air could bypass over the ricks and exit through the cupola in the roof of the rickhouse.

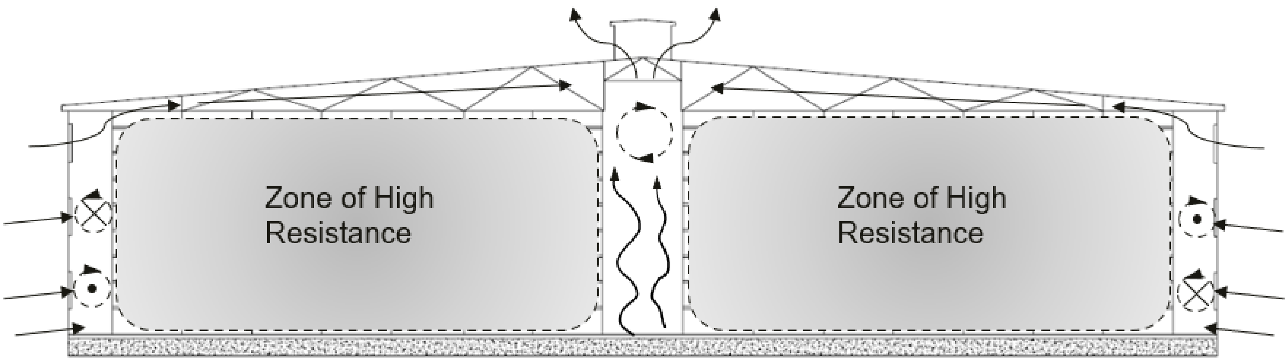

Figure 10. Rickhouse Section View Airflow Patterns.

The walkway between the ricks was generally isolated. As discussed earlier, no air entered through the main entrance. As a result, air naturally rose due to the temperature differential between the concrete floor and ambient air (see the center area of the building section in Figure 10). Air recirculation above the central walkway was noticeably faster than other recirculation patterns and was likely caused by the mixing of the air bypassing over the ricks and the air rising from the central walkway. Eventually, this air exited the rickhouse through the cupola. The air inside the ricks appeared to be stagnant or very slowly recirculating. Smoke tests could not verify air movement inside the ricks as recirculation, although there was likely very subtle migration in and out of the ricks over time. The high resistance due to the presence of ricks, i.e., the zone of high resistance in Figure 10, removed the agitation that would normally be present and allows for the separation of the air due to density. This separation occurred due to the natural phenomenon by which humid air has a lower density than dry air and will, therefore, rise at the top of a closed structure.

As represented in Figure 11, air with higher humidity rose to the top of the ricks. Because the surveyed rickhouse had been recently built, its ricks were not stocked with bourbon barrels for maturation. When this rickhouse is eventually filled with barrels, the presence of ethyl alcohol vapor will be added to the internal atmosphere through leaks in the barrels. This ethyl alcohol will then accumulate on the floor of the rickhouse as alcohol-laden air is heavier than dry air. Due to this rickhouse's uniquely designed ground vents, which intersect the floor and the walls, there is no confinement or seal at the floor of the rickhouse. This allows for air at the floor of the walkways and near the ground vents to leave the rickhouse. This may provide an opportunity for ethyl alcohol to migrate out of the ricks, into the walkway, and out of the rickhouse.

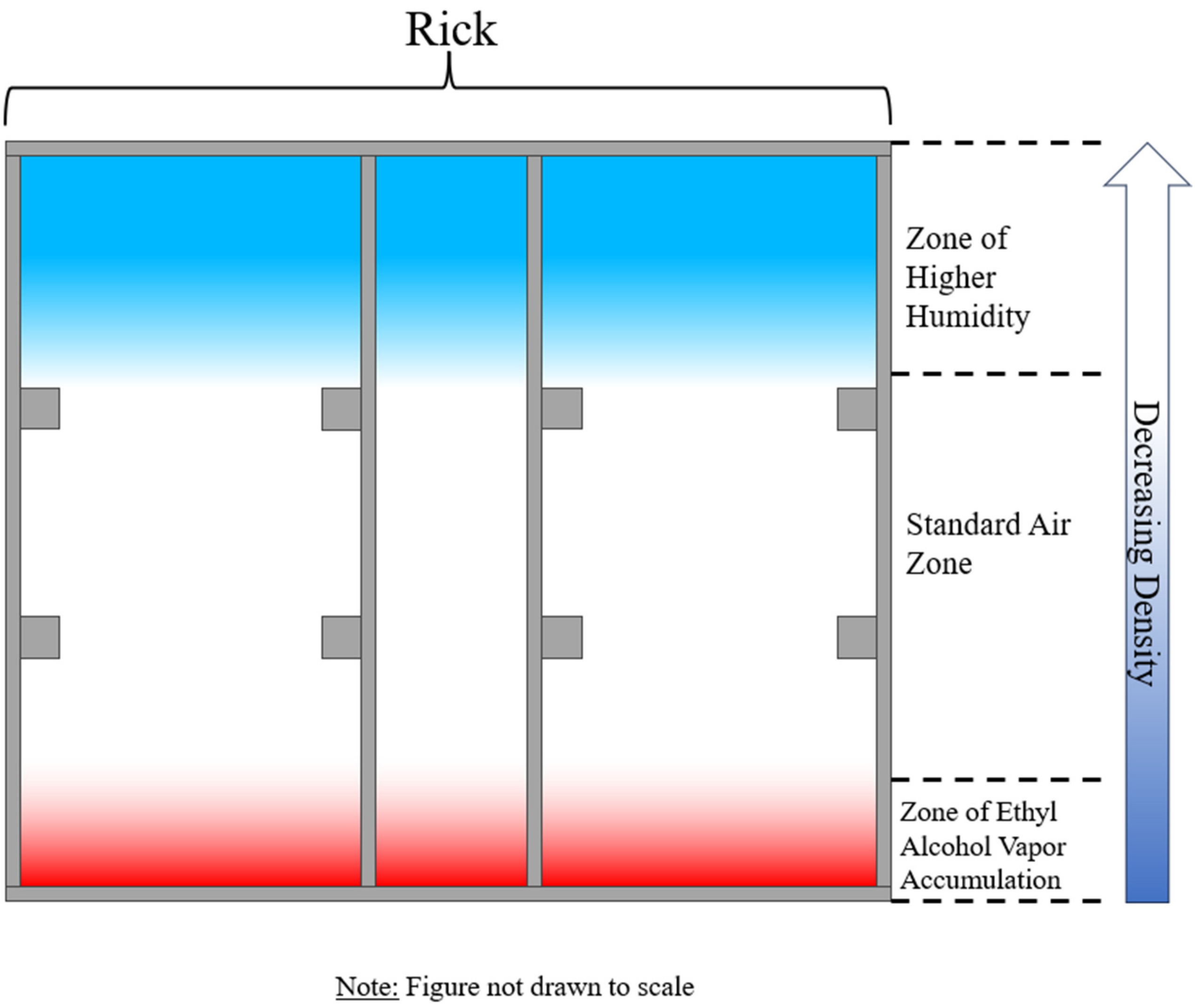

Figure 11. Density Zones of a Rick (Figure not drawn to scale).

5. Conclusions

Experimental findings utilizing both differential pressure measurement and smoke tracing techniques have shed significant light on the airflow dynamics within the rickhouse. Through the observation of these techniques, it became evident that the empty ricks provided pockets of high resistance, with stagnant air and minimal recirculation. This explains why the air entering the rickhouse through the side windows and ground vents would not migrate into the ricks but rather exit through another window or vent. Notably, these ricks housed no bourbon barrels; it is likely then that the high resistance provided by the ricks would increase significantly when the ricks are full. Additionally, if filled barrels were present, it would be expected that the leaking ethyl alcohol would accumulate at the bottom of the ricks due to the higher density and the fact that the air is stagnant.

Further insights gained from the experiment were the nature of the air entering and leaving the building due to natural ventilation. From the smoke tests performed, air enters the building through the side windows and ground vents, flows down the side hallways, and exits through another set of windows. Air flowing into the windows at the top of the rickhouse can ingress further into the rickhouse by bypassing over the top of the high-resistance ricks and exiting through the cupolas. Air was found not to be entering or exiting through the main entrance.

The research performed is the first step to bridge the gap in research into the storage structures of alcohol spirits. This research provides context for possible further corrosion mitigation. By identifying the airflow patterns that contribute to ethyl alcohol accumulation, further research can be focused on possible solutions to corrosion mitigation in bourbon rickhouses. However, constraints on research access limit the number of times this type of study can be performed. Specifically, smoke tracing, a critical component of this study, can only be performed when the warehouse is empty to prevent any potential effect on the product, and companies often fill warehouses within a few weeks of their construction.

Additional testing should be performed to capture other factors affecting airflow within rickhouses. Temperature can greatly affect natural ventilation; testing the same or similar locations at warmer temperatures would be ideal, as this study was conducted during cooler temperatures. Smoke tracing proved a more effective technique than differential pressure monitoring, as the airflow within the rickhouse was subtle and often below the accuracy range for the instrument used, although the effective zero differential pressure measurements by the instrument utilized matched areas of very little or no airflow. Given the opportunity, further differential pressure surveys should be performed in other warehouses, either empty or filled.

Author Contributions: S.J.S.: conceptualization, investigation, methodology, project administration, resources, supervision, and writing—review and editing. M.W.L.: conceptualization, investigation, methodology, writing—original draft, writing—review and editing, and visualization. Z.E.W.: investigation, and writing—review and editing. B.M.D.: investigation and writing—review and editing. Z.A.: writing—review and editing, corresponding author. All authors have read and agreed to the published version of the manuscript.

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References

1. Conner, J. 'Chapter 16—Maturation'. In *Whisky and Other Spirits*, 3rd ed.; Russell, I., Stewart, G.G., Kellershohn, J., Eds.; Elsevier Ltd.: Amsterdam, The Netherlands, 2022; pp. 291–311. [CrossRef]
2. Philp, J.M. Cask quality and warehouse conditions. In *The Science and Technology of Whiskies*; Piggott, J.R., Sharp, R., Duncan, R.E.B., Eds.; Longman Scientific & Technical; J. Wiley: Hoboken, NJ, USA, 1989; ISBN 9780582044289.
3. Campari Group. Sustainability Report. 2023. Available online: https://www.camparigroup.com/en/page/sustainability (accessed on 11 November 2024).
4. Suntory. Sustainability Report. 2023. Available online: https://www.suntoryglobalspirits.com/news/suntory-global-spirits-releases-2023-sustainability-report (accessed on 11 November 2024).
5. United Nations. The 17 Goals | Sustainable Development. United Nations. 2024. Available online: https://sdgs.un.org/goals (accessed on 3 December 2024).
6. Lstiburek, J.W.; Eng, P. Some old lessons distilled. *ASHRAE J.* **2008**, *50*, 82–84.
7. Browning, M. The effects of temperature on major beer compounds during barrel maturation. *Master Brew. Assoc. Am.* **2014**, *51*, 12–18. [CrossRef]
8. Demoranville, L.; Heist, P. The Chemistry of Bourbon. *Chem. Eng. Prog.* **2021**, *117*, 40–45.
9. Macy, T. Barrel Maturation. Tom Macy Cocktails. 2020. Available online: https://www.tommacy.com/barrelmaturation (accessed on 11 November 2024).
10. Jedermann, R.; Borysov, M.; Hartgenbusch, N.; Jaeger, S.; Sellwig, M.; Lang, W. Testing Lora for food applications-Example application for airflow measurements inside cooled warehouses with apples. *Procedia Manuf.* **2018**, *24*, 284–289. [CrossRef]
11. Praeger, U.; Jedermann, R.; Sellwig, M.; Neuwald, D.A.; Hartgenbusch, N.; Borysov, M.; Truppel, I.; Scaar, H.; Geyer, M. Airflow distribution in an apple storage room. *J. Food Eng.* **2020**, *269*, 109746. [CrossRef]
12. Brinks, P.; Kornadt, O.; Oly, R. Air infiltration assessment for industrial buildings. *Energy Build.* **2015**, *86*, 663–676. [CrossRef]
13. Iordache, V.; Iordache, F. Air permeability measurements in a Deep Freeze Warehouse. *Energy Procedia* **2017**, *112*, 489–496. [CrossRef]
14. Lackermeier, U.; Rudnick, C.; Werther, J.; Bredebusch, A.; Burkhardt, H. Visualization of flow structures inside a circulating fluidized bed by means of laser sheet and image processing. *Powder Technol.* **2001**, *114*, 71–83. [CrossRef]
15. Xilin, W.; Quanlin, F.; Yincheng, G. Visualization of two-phase turbulent jet coherent structures. In Proceedings of the International Symposium on Multiphase Flow (ISMF'97), Beijing, China, 7–11 October 1997; International Academic Publishers: Lausanne, Switzerland, 1997; pp. 344–350.
16. Chlebanowski, J.S.; Bodapati, S. Flow Visualization by Laser Sheet. Ph.D. Thesis, Naval Postgraduate School, Monterey, CA, USA, 1988.
17. Merzkirch, W.; Gersten, K. *Techniques of Flow Visualization*; Technical Report AGARD-AG-302; Advisory Group for Aerospace Research and Development, NATO: Brussels, Belgium, 1987.
18. Meng, X.; Liu, F.; Luo, S. Effect of low dorsal fin on the breakdown of vortices over a slender delta wing. *Aerosp. Sci. Technol.* **2018**, *81*, 316–321. [CrossRef]
19. Walker, I.S.; Claret, V.; Smith, B. *Laser Sheet Light Flow Visualization for Evaluating Room Air Flows from Registers*; Technical Report; US Department of Energy, Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2006. [CrossRef]
20. Del Rio ER, V.; Woiski, E.R.; Gasche, J.J.; Mansur, S.S.; Vieira, E.D.R. Vortex Formation in Incompressible Axisymmetric Free Jets. *Rev. De Eng. Térmica* **2014**, *13*, 74–80. [CrossRef]
21. Yadav, A.P.; Nishikata, A.; Tsuru, T. Electrochemical impedance study on galvanized steel corrosion under cyclic wet–dry conditions—Influence of time of wetness. *Corros. Sci.* **2004**, *46*, 169–181. [CrossRef]
22. Bhola, S.M.; Bhola, R.; Jain, L.; Mishra, B.; Olson, D.L. Corrosion behavior of mild carbon steel in ethanolic solutions. *J. Mater. Eng. Perform.* **2011**, *20*, 409–416. [CrossRef]
23. McPherson, M.J. *Subsurface Ventilation Engineering*, 2nd ed.; Mine Ventilation Services Inc.: Fresno, CA, USA, 2009.
24. TSI. *DP-Calc™ Micromanometer Model 5815 Operation and Service Manual*; TSI: Shoreview, MN, USA, 2016.
25. ASHRAE. *Fundamentals: An Instrument of Service Prepared for the Profession Containing a Technical Data Section of Reference Material Pertaining to Systems for Heating, Refrigerating, Ventilating, and Air Conditioning*; Handbook; American Society of Heating Refrigerating and Air-Conditioning Engineers: Peachtree Corners, GA, USA, 1981.