Energy and airflow optimization in an industrial roasting system: A case study

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Abstract. This study presents an energy and airflow optimization of industrial drum coffee roasting system, focusing on the influence of airflow on heat transfer, particulate transport, and operational safety. Measurements revealed significant deviations from design conditions, with airflow velocities of 12.3 m/s leading to insufficient transport of coffee chaff and accumulation of deposits within the ductwork, increasing pressure losses and fire risk. In contrast, stable operation was achieved at approximately 19.3 m/s (5583 m³/h), which ensured effective particulate transport and prevented deposition. Based on these findings, a phase-dependent airflow control strategy was developed and implemented using a variable speed drive (VSD), maintaining maximum airflow during the first crack phase and reduced airflow during other stages. This approach improved process stability and thermal performance while reducing energy consumption. The transition from damper-based control to fan speed regulation resulted in energy savings of approximately 51% (3713 kWh/year). In addition, reduced airflow during non-critical phases minimized underpressure in the roasting area and improved overall ventilation balance. The results provide a quantitative basis for airflow design and control in industrial coffee roasting systems.

1 Introduction

Coffee roasting is a complex thermofluid process based on heat and mass transfer, where airflow plays a key role in determining both the thermal characteristics and the quality of the product. During roasting, coffee beans undergo a series of physical and chemical transformations. These changes typically occur during the drying, Maillard, and development phases, with the first crack occurring at approximately 190–200°C [1–3]. These transformations include moisture evaporation, structural changes, and exothermic reactions, which significantly influence the temperature-time profile of the process [2, 3].

Various experimental and numerical studies show that convective heat transfer is dominant, governing the energy exchange between the hot gases and the coffee beans in drum roasters [1, 2]. It has been established that the heat transfer coefficient is highly dependent on airflow conditions. As a result, insufficient airflow leads to reduced heat transfer, delayed grain temperature rise, and uneven roasting [1, 4]. Furthermore, the airflow influences the

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development of the bean transformation by controlling the rate of moisture removal and the release of volatile compounds, which are essential for flavor formation [3, 4].

Different modelling approaches, including computational fluid dynamics (CFD), demonstrate that the airflow distribution within the roasting chamber (drum) significantly influences temperature uniformity and roasting kinetics [5]. These studies emphasize that both the amount and distribution of airflow are critical parameters for achieving consistent roasting conditions. However, most of the available studies are limited to controlled or laboratory environments and do not fully capture the complexity of industrial systems.

In industrial drum coffee roasters, the airflow plays a critical role in the transport of solid particles, primarily coffee chaff, which is separated during the first stage of roasting. According to established principles of industrial ventilation, a minimum transport velocity is required to ensure effective transport of solid particles and to prevent their deposition in the air ducts. For particles of average density, transport velocities in the range of 18–20 m/s are typically required [6]. Operating below this threshold leads to settling, particle accumulation, and an increased risk of system fouling and fire. For follow-up filtration, the particle entry velocity into the cyclone separator is also important.

Pressure losses further influence the performance of exhaust systems in the ducts and fittings, which depend on the airflow rate, the geometry of the ducts, and the system configuration. Particle deposition on the surface of the air ducts affects linear and local pressure losses, which should be adequately assessed. This contamination can significantly reduce airflow and cause deviations from design parameters, leading to a decrease in the quality of the roasted coffee.

Despite the importance of airflow, there is a lack of experimental studies linking airflow velocity, heat transfer efficiency, particle transport, and system safety in full-scale industrial roasting systems. Existing studies focus primarily on thermal behavior or product quality, without integrating ventilation performance and operational reliability. Similar approaches, combining experimental measurements, environmental analysis, and numerical modelling, are widely applied in energy and thermal systems to assess performance, degradation mechanisms, and optimization potential under real operating conditions [7–12].

This study addresses this gap through an experimental investigation of an industrial drum coffee roasting system, including airflow measurements using the velocity-area method with a Pitot tube in accordance with ISO 3966 [13] and ASHRAE Standard 41.2 [14], supplemented by infrared thermographic analysis. The objectives are (i) to evaluate the airflow conditions and identify deviations from design parameters, (ii) to determine the minimum airflow required for stable and safe operation, and (iii) to develop a phase-dependent airflow control strategy utilizing variable-speed fan operation. The study further evaluates the impact of the proposed solution on the energy consumption of the exhaust system.

2 Materials and methods

2.1 Description of the existing industrial coffee roasting system

The study was conducted in late 2018, while the reconstruction of the existing industrial coffee roasting installation in Sofia, Bulgaria, was completed in early 2019. The coffee production line consists of three roasting units: Roaster 1, Roaster 2, and Roaster 3. Roaster 1 and 2 are identical; Roaster 3 is different - a smaller one. Each coffee roaster (Figure 1) is connected to a separate exhaust system for flue gas extraction and also operates with a dedicated burner and generates a mixture of hot air, combustion gases, and particulate matter (coffee chaff), which is transported through a ductwork and extracted by a suction fan. Before the coffee chaff is released into the atmosphere, the flue gas is filtered through a cyclone separator, and the remaining particles are burned in an additional afterburner.

a)

b)

Fig. 1. Existing industrial drum roaster for coffee (a) and an infrared thermographic image (b) captured with a FLIR E6 thermal imaging camera during steady-state operation. The thermal image shows the temperature distribution and highlights areas of heat loss and potential insulation deficiencies.

The exhaust system of each roaster includes both circular and rectangular air ducts and a control damper. During operation, the system operates at high temperatures (up to 300°C) and particulate loading, which influence airflow characteristics and pressure losses. Prior observations indicated the presence of particulate deposition of coffee chaff within the ductwork (Figure 2), suggesting insufficient transport velocities and non-optimal ventilation performance. One of the major problems in the system was the accumulation of particulate deposits on the inner surfaces of the ductwork increases the risk of ignition, as sparks generated in the roasting drum are transported by the airflow and initiate combustion. Such events are leading to interruption of the production process, requiring replacement of the fan, and cleaning of the ductwork system.

a)

b)

Fig. 2. Existing round suction ductwork with the control damper (a). Existing rectangular exhaust ductwork after the suction fan (b).

As it is illustrated on Figure 1 and Figure 3 infrared thermographic analysis was performed using a FLIR E6 thermal imaging camera to evaluate the thermal condition of key system components, including roasting drums, ducts, fans, and insulation surfaces. Thermographic inspections were conducted during steady-state operation of the roasting units. The camera's automatic hot-spot detection function was used to identify areas with elevated surface temperatures. The obtained thermal images were analysed to detect insulation defects, heat losses, and non-uniform temperature distributions across system components.

2.2 Airflow measurement methodology

The first step in identifying the problem was to measure the airflow rate in the various operating modes. Therefore, airflow measurements were performed using the velocity–area method with a Pitot tube, in accordance with ISO 3966:2008 and ASHRAE Standard 41.2. A stainless-steel Pitot tube (Dwyer 160 type) coupled with differential pressure instruments (testo 512-2 and testo 510i) was used to determine the dynamic pressure and calculate local air velocities. Measurement points were distributed across the duct cross-sections following standardized traversing schemes for circular ducts. At each point, the local velocity was determined based on the measured differential pressure, and the average velocity was calculated as the arithmetic mean of all measured values. The volumetric flow rate was then obtained using the cross section and the average speed. To account for the elevated temperature of the flue gases, corrections were applied to the measured velocities using the actual gas density, determined from the measured temperature. This correction is necessary, as the measuring instruments assume standard air density (1.2 kg/m³). The corrected airflow parameters are therefore considered representative of real operating conditions.

2.3 System optimization approach

Based on the measured airflow parameters and the identified operational issues, a strategy was developed to optimize both the airflow and the control of the exhaust system. Insufficient airflow velocity results in inadequate transport of coffee chaff, leading to deposition in the air duct system and an increased risk of ignition. Initial observations identified a critical airflow velocity of 19 m/s, which falls within the 18–20 m/s range from the reviewed literature [6] as the minimum requirement for stable operation during transport. In the original system configuration, the exhaust fan operated at a constant (fixed) speed, and the airflow was regulated using dampers. This type of control leads to energy losses, not only in the exhaust system to the rotary drum roaster, but also because part of this air creates negative pressure in the production room, increasing the costs of maintaining the microclimate parameters within it. To overcome these limitations, the system was modernized by installing a new exhaust fan equipped with a VSD (Figure 3). This allows for direct control of the airflow by adjusting the fan speed, replacing the previous control strategy based on mixing with dampers.

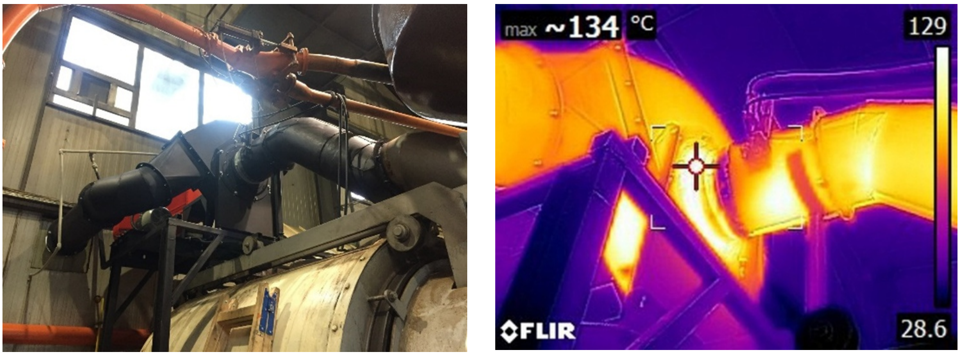

Fig. 3. New exhaust fan MZ Aspiratori TYPE GF560/T.

The frequency converter was configured to operate in open-loop frequency control mode, where fan rotational speed is adjusted according to predefined roasting stages rather than through closed-loop feedback. The control variable is the airflow demand associated with each process phase, implemented through fixed frequency setpoints. Accordingly, the fan frequency is increased during the first crack stage to maintain the required transport velocity for coffee chaff removal and reduced during the remaining stages to improve thermal efficiency and reduce energy consumption.

An airflow control strategy was developed and presented in Figure 4 that allows the airflow to be adjusted according to the requirements of the roasting process. During the first crack, high airflow rates are applied to ensure efficient transport of the coffee chaff, while during the other stages, a reduced airflow is used to improve the thermal efficiency of the roaster and minimize the energy consumption of the exhaust system and heat losses from ventilation in the production area.

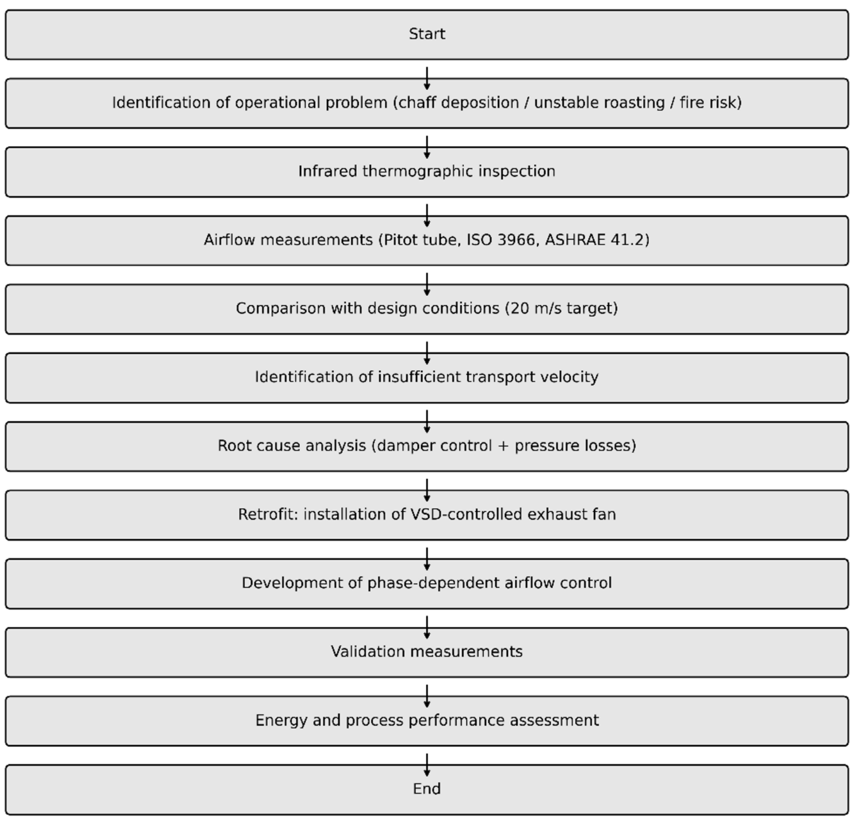

Fig. 4. Flowchart of the testing and troubleshooting procedure applied for airflow diagnosis, retrofit implementation, and validation of the industrial coffee roasting system.

3 Results and Discussion

The analysis is focused on two identical industrial drum coffee roasters (Roaster 1 and Roaster 2), allowing a direct comparison of airflow conditions and their impact on system performance. A schematic representation of each one is presented in Figure 5. Each roaster is connected to an exhaust system consisting of extract and exhaust ducts, a centrifugal fan, a cyclone separator, an afterburner, and a chimney. The system operates under high-temperature conditions, with flue gas temperatures reaching 250–300°C, and transports a mixture of combustion gases, hot air, and solid particles (coffee chaff).

Airflow measurements performed in accordance with [13, 14] reveal significant deviations from the recommended conditions for particulate transport. The average air velocity in the exhaust duct of Roaster 1 under operating conditions (at the time of first crack) was approximately 7.6 m/s, while the corrected velocity, accounting for gas temperature, reached 12.3 m/s. The corresponding volumetric airflow was 4052 m³/h. In contrast, Roaster 2 exhibited substantially higher airflow performance, with velocities in the range of 18.2–18.8 m/s and airflow rates exceeding 5300 m³/h. These values are consistent with recommended transport corrected velocities for medium-density particulate matter (18–20 m/s), according to [6], indicating significantly improved operational conditions.

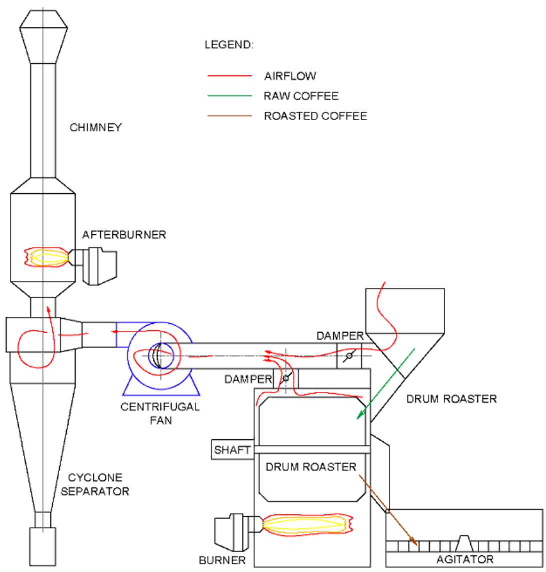

Fig. 5. Schematic diagram of an industrial drum coffee roaster system.

The insufficient airflow velocity in Roaster 1 explains the observed accumulation of particle deposits in the air duct system, where layers of contamination with thickness from 5 to 10 mm have been identified (Figure 2). This confirms that low airflow velocities lead to particle deposition and progressive fouling of the exhaust system. In contrast, the higher velocities in Roaster 2 allow for effective transport of solid particles, resulting in cleaner air ducts and more stable operation. The original system was designed to operate at airflow velocities of 20 m/s; due to system resistance, duct contamination, and non-optimal control, the actual operating conditions in Roaster 1 deviate significantly from the design values. These findings highlight the critical importance of maintaining adequate airflow velocity in exhaust systems loaded with particles, as even small deviations below the recommended threshold can lead to increased pressure losses, reduced efficiency, and an elevated risk of fire.

In the initial configuration, the exhaust fan operated at a constant speed, while airflow control was achieved using dampers. This leads to increased pressure drops due to local resistance and reduced control accuracy, which in turn affects the thermal process in the roaster drum and increases energy consumption. To address these issues, the system was modernized by installing a new exhaust fan with a maximum electrical power of 5.5 kW, equipped with a frequency converter. The modernized system allows for direct control of the airflow by adjusting the fan speed, enabling operation at 25 Hz resulting in 2.5 kW electrical power under optimal conditions. At this operating point, the measured airflow parameters correspond to approximately 5583 m³/h and 19.3 m/s, which fully meets the design requirements and ensures stable system operation. The measured airflow parameters have a direct impact on the thermal behaviour of the roasting process and the resulting temperature variation in the drum roaster. Figure 6 presents a comparison between the reference roasting profile (based on literature data), and the observed performance of the two systems operating under different airflow conditions.

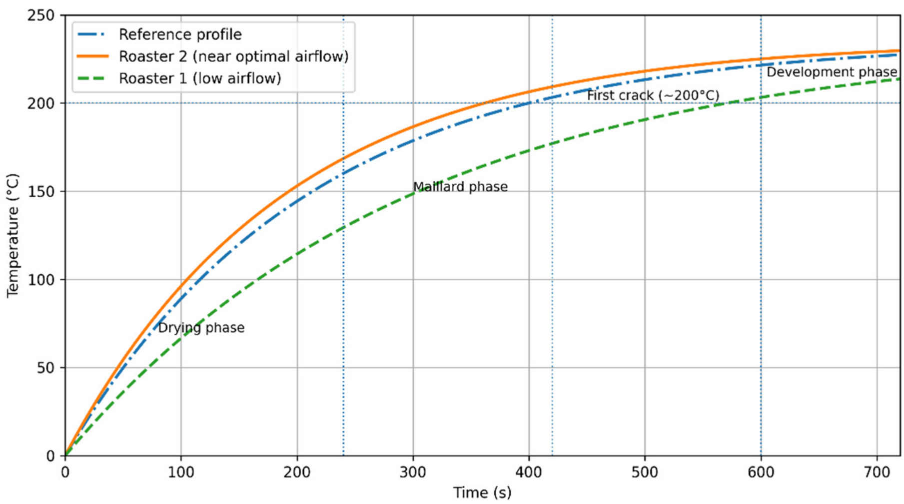

Fig. 6. Temperature–time roasting profiles for two industrial drum roasters compared to a literature reference. Roaster 2 (near-optimal airflow) closely follows the ideal profile, while Roaster 1 (low airflow) shows a slower temperature rise and delayed first crack (~200°C), highlighting the effect of airflow on heat transfer and roasting behaviour.

The reference curve represents typical roasting conditions characterized by controlled temperature increase and the occurrence of the first crack at 200°C. Under these conditions, sufficient airflow ensures effective convective heat transfer between the hot gases and the coffee beans. Roaster 2, operating at airflow velocities of 18.2–18.8 m/s (about 5300 m³/h), follows the reference profile closely. The temperature increases steadily, reaching the first crack within the expected time range (only 8.6% delay), indicating stable heat transfer conditions and proper process control. On the other hand, Roaster 1, operating at significantly lower airflow velocities (12.3 m/s, 4050 m³/h), exhibits a noticeably slower temperature rise. This results in a delayed approach of 54.1% to the first crack temperature (200°C), indicating reduced heat transfer rates and altered roasting kinetics. The deviation from the reference profile confirms that insufficient airflow leads to non-optimal thermal conditions within the roasting chamber. These findings are consistent with previous studies reporting the dominant role of convective heat transfer in coffee roasting systems [1, 2, 4].

The airflow requirements vary during the different stages of the roasting process due to changes in heat and mass transfer conditions and the generation of particulate matter. During the drying phase, moderate airflow is maintained to remove evaporated moisture from the coffee beans while limiting excessive convective heat losses. During the Maillard phase, airflow is gradually increased to enhance convective heat transfer and support the removal of released volatile compounds. During the first crack phase, maximum airflow is applied because this stage is associated with rapid release of coffee chaff and increased particulate transport requirements; maintaining sufficient transport velocity prevents deposition in the duct system and ensures stable and safe operation. During the development phase, airflow is reduced again to maintain thermal stability, avoid excessive cooling of the roasting chamber, and improve overall energy efficiency while preserving adequate exhaust conditions.

Based on the experimental findings, a phase-dependent airflow control strategy was developed to optimize both process performance and system reliability. The proposed approach is presented in Figure 7 and is based on maintaining airflow conditions that satisfy both heat transfer and particulate transport requirements during the different stages of the roasting process.

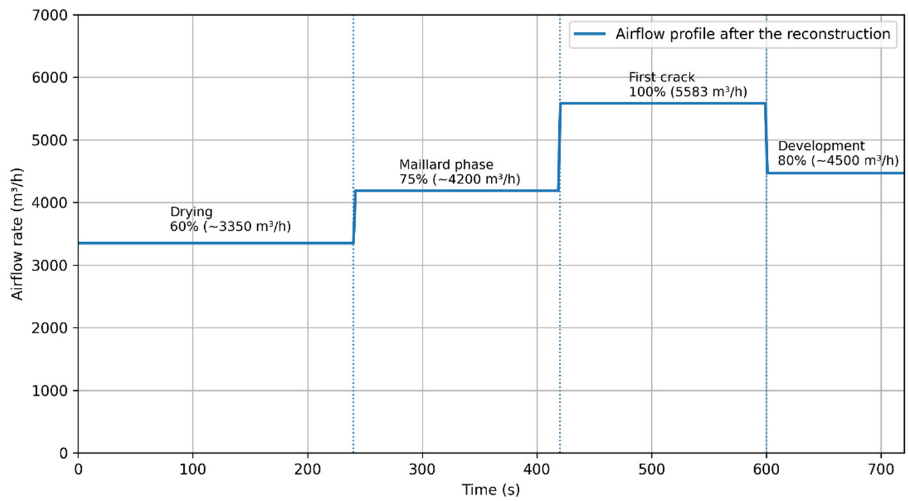

Fig. 7. Recommended airflow profile during roasting and corresponding airflow requirements during drying, Maillard, first crack, and development phases. Maximum airflow is maintained during first crack to ensure effective coffee chaff transport and stable operation.

The recommended airflow distribution is defined as follows: 60% of the maximum airflow during the drying phase, 75% during the Maillard phase, 100% during the first crack phase, and 80% during the development phase. These values correspond to airflow rates of 3350 m^3/h, 4200 m^3/h, 5600 m^3/h, and 4500 m^3/h, respectively. Experimental data shows that the airflow needed for cooling the drum roaster is 3548 m^3/h.

This strategy is implemented using a variable-speed drive (VSD), which allows for direct control of the fan speed and, consequently, the airflow rate. Under optimal operating conditions, the VSD operates at a predefined frequency setpoint of 25 Hz corresponding to the required airflow of approximately 5600 m^3/h during the first crack stage. Dynamic airflow control reduces energy consumption. The proposed airflow profile is consistent with general coffee roasting practices described in the literature, where the airflow increases gradually during the roasting process. However, unlike qualitative or percentage-based approaches, this study provides a quantitative determination of airflow requirements based on measured system performance and validated operating thresholds.

In terms of energy consumption, variable-speed control significantly improves the efficiency of the exhaust system. In the original configuration, the exhaust fan operated at a constant speed (2.5 kW) with airflow regulated by dampers, resulting in continuous operation at full load and the associated energy losses. Based on typical operation of 32 roasting cycles per day (2912 hours/year), annual energy consumption is 7280 kWh. After the retrofit, the airflow is controlled directly by adjusting the fan speed, which reduces the average power requirement to 49% of the nominal value and lowers annual energy consumption to 3567 kWh. This corresponds to energy savings of 3713 kWh per year (51%). Furthermore, the reduced airflow during non-critical phases lowers the negative pressure in the production room, limiting uncontrolled air infiltration from outside, thereby improving the microclimate parameters within the room and reducing the energy costs associated with maintaining them.

4 Conclusion

This study presents an experimental analysis and optimization of energy consumption and airflow in an industrial drum coffee roasting system. The results show that airflow conditions are critical for both process efficiency and safe operation. Measurements indicate that airflow velocities of approximately 12.3 m/s are insufficient for particle transport, leading to the accumulation of coffee chaff in the ductwork. Stable operation is achieved at 19.3 m/s (5583 m^3/h), which ensures effective transport and prevents deposition. A critical airflow threshold of approximately 19 m/s has been identified as the minimum requirement for reliable operation, as lower velocities lead to particle deposition, increased pressure losses, and an elevated fire risk.

A phase-dependent strategy for airflow control has been developed and implemented, using a new VSD-driven exhaust fan, which allows the airflow to be adjusted according to the roasting process. This approach maintains maximum airflow during the first cracking phase and reduces airflow during the other phases, improving both process stability and energy performance. The transition from control based on volume dampers to fan speed control results in energy savings of approximately 51% (3713 kWh/year) for a single production line, 32 cycles per day, 7 days a week. Additionally, the reduced airflow during non-critical phases minimizes negative pressure in the production area, improving ventilation balance and the overall efficiency of the microclimate control system. The results provide a quantitative basis for airflow design and demonstrate that maintaining an adequate airflow velocity is essential for the safe and efficient operation of industrial drum coffee roasters.

Future work will focus on further development of the airflow control strategy through implementation of automated process control based on real-time operating conditions. Additional studies will investigate closed-loop control using temperature, pressure, or airflow measurements, as well as integration of particulate monitoring to further improve operational reliability and fire prevention. Future research will include numerical modelling and CFD analysis to optimize airflow distribution and heat transfer in industrial roasting systems and to evaluate the relationship between airflow conditions and final product quality.

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