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ABSTRACT

The main objective of the present work was to assess the effects of sequential air ventilation on: (i) the working conditions of an industrial large-scale ripening room used for PDO Saint-Nectaire cheese ripening, (ii) the reduction of electrical energy consumption, (iii) the evolution of cheese ripening dynamics and final quality. Six ripening trials were performed: 2 with continuous ventilation (reference conditions), 2 with time-based sequential ventilation, and 2 with temperature-based sequential ventilation.
The main findings are as follows:

- Cheese ripening caused substantial respiratory activity. This activity was not significantly affected by either continuous or sequential room ventilation procedure. Air renewal and door opening were identified as the two major factors acting on the amount of CO_2 and O_2 measured in the room.
- In the conditions of this study, mean economy on electrical energy consumption when adopting temperature-based sequential ventilation with a temperature variation range close to 0.7°C reached 125 kWh per day and corresponded to a 0.42% increase in ripening room productivity.
- Finally, sequential ventilation had no significant effect on ultimate cheese quality: focusing on ripening microbial flora, the main biological characteristics of the cheese, and sensory descriptors, there was little evolution versus ripening time compared to continuous ventilation.

Keywords: industrial cheese ripening room; sequential air ventilation; energy consumption; productivity

INTRODUCTION

Industrial cheese ripening is often performed in very large rooms of up to 2,000 m^3, in which air temperature and relative humidity (RH) are controlled automatically. These ripening rooms benefit from substantial continuous ventilation to ensure optimum homogeneity of the air conditions and even ripening of the cheese products. The energy costs tied to ventilation account for about 50% to 55% of total ripening costs.
Part of the integrated European 'Truefood' project was dedicated to studying ripening room management strategies that aimed at reducing energy costs, particularly by adopting sequential ventilation systems. In a first study [1], results obtained on two types of cheeses – a pressed non-cooked cheese and a cooked hard cheese – showed that significant improvements could be achieved in terms of cheese ripening room monitoring and control using sequential air ventilation (air circulation cut off for 10 min every 15 min or for 6 min every 10 min) in small-sized ripening rooms (from 4.6 m^3 to 15 m^3). The results [1] demonstrated that:

- cheese ripening dynamics in terms of microbial and biochemical aspects were not significantly modified compared to continuous air ventilation,
- final cheese quality in terms of sensory aspects was similar between continuous and sequential air ventilation,
- using sequential air ventilation is expected to bring a 14% reduction in energy consumption.

Building on these findings, it was proposed to applied the same strategy to a large-scale industrial ripening room (1290 m^3: 20.8 m long, 12.4 m wide and 5 m high) in which an absolute maximum of 19,150 PDO Saint-Nectaire cheeses are ripened over at least 4 weeks. The objectives of the second and last step of this 'industrial-scale' study were i) to test a new ripening room system based on sequential air ventilation, and ii) to determine the savings in terms of electrical energy consumption resulting from these new ventilation conditions.

MATERIALS & METHODS

The industrial ripening room selected in this study is currently used to ripen traditional PDO Saint-Nectaire cheeses. It is a very large room capable of ripening a maximum of 19,150 cheeses, and is equipped with automatic air temperature and RH controllers and two air-conditioning systems working in parallel, each including one dual-helicoidal fan. We designed and produced a lab prototype integrating the most significant measurements (air temperature, RH, CO_2 and O_2 contents, electrical energy consumption, cheese mass) and automatically controlling ripening room conditions. CO_2 and O_2 sensors, used to determine the composition of the ripening room atmosphere and calculate respiratory activity, together with temperature (T) and RH probes were located in a temperature-controlled cabinet located outside the ripening room. The sensors were fed by gas sucked from a space in the chamber that was deemed representative of chamber atmosphere. Electrical energy consumption was measured with a power analyzer located in the cabinet. Other data was directly recorded by the computer system controlling the industrial cheese-making plant, i.e. dry and wet air temperatures (Td and Tv, respectively), percentage opening of the 3-way valve monitoring ripening room cooling (%V), percentage of electric power consumed by the heating resistances (%T) monitoring ripening room heating. Furthermore, in-house software (CRiC 2.0, 2007, registration No. IDDN.FR. 001.490043.000.R.X.2007. 000.30600) was specially adapted for monitoring this industrial prototype and used to control air ventilation regime, i.e. either continuous or sequential, and either time-controlled or temperature-controlled.

Over one year, six different PDO Saint-Nectaire ripening trials were performed, as follows:

- two reference trials, called Ref1 and Ref2, with continuous air ventilation (CV) of the ripening room that corresponded to the routine working conditions used by the industrial company.
- two trials with “time-based” sequential ventilation of the ripening room. The first trial, called SV50, was run with 50% of ripening time without ventilation and the other 50% with ventilation. The second trial, called SV60, was run with 60% of ripening time without ventilation and the other 40% with ventilation. In SV50, the base cycle was 1 h long, with 30 min ventilation on and 30 min ventilation off. In SV60, the base cycle was 75 min long, with 30 min ventilation on and then 45 min ventilation off.
- and two trials with “temperature-based” sequential ventilation of the ripening room, called SVRT1 and SVRT2. Since temperature increased when the air ventilation is cut off and decreases when air circulation is switched back on, there was the possibility to define a temperature interval, bounded by high and low set-points temperatures, within which air ventilation could be modulated. Consequently, ventilation time is a function of the thermal behaviour of the ripening room. During these two trials, three temperature intervals, equal to 0.3, 0.7 and 1.0°C, were studied.

Each of these six trials was led for 28 days (4 weeks) to fit routine PDO Saint-Nectaire ripening. Two cheeses were sampled on day 1 and then every week. The microbial, biochemical and sensory evolution of the sampled cheeses was analyzed as described previously [1].

RESULTS & DISCUSSION

The effect of sequential air ventilation in the ripening room was assessed through 3 main factors:

- cheese respiratory activity,
- energy consumption,
- evolution of Saint-Nectaire ripening dynamics and final product quality.

Cheese respiratory activity

As shown by the variations in CO_2 and O_2 concentrations recorded in the ripening room, PDO Saint-Nectaire ripening was also accompanied by substantial respiratory activity, especially when a high number of cheeses were being ripened in the room. Nevertheless, CO_2 and O_2 concentrations were closely related to room monitoring patterns, especially the opening and closing of the room door and air renewal.

In trials where air renewal was activated, CO_2 concentration in the room always remained less than 1%, and most of the time was less than 0.5%. In parallel, O_2 concentration varied slightly around 20%. These concentrations are typical of ripening trials performed with air renewal, and were also observed with continuous air ventilation.

However, in trials without air renewal, there were significant variations in O_2 and CO_2 concentrations, especially during periods corresponding to the ends of week, where the door of the ripening room stayed

closed and where CO_2 concentration increased to 3.5% while, in parallel, O_2 concentration decreased from 20% to around 17.5%. During working days each week, there was a small successive rise and fall in CO_2 concentration (and conversely for O_2 concentration) with values ranging from 0.5% up to 1.8% (and 20% down to 18.5% for O_2 concentration). The increases in CO_2 concentration corresponded to night-time when the door stayed closed, while the decreases corresponded to the work day when the door is regularly open. The same pattern of results was obtained when the ripening room was under continuous ventilation.
In conclusion, cheese ripening created significant respiratory activity. This activity was not significantly affected by ripening room ventilation regime, whether continuous or sequential. Air renewal and door opening were identified as the two most important factors acting on the amount of CO_2 and O_2 measured in the room.

Electrical energy and cooling energy consumption

Preliminary trials carried out in order to test the room under sequential ventilation showed that ripening room heating was responsible for a large share of electrical energy consumption. This heating was automatically monitored by the room temperature control device which also was controlling the 3-way cooling valve. Consequently, electrical energy expenditure increased because a proportion of the cooling energy was being consumed to counterbalance the heat energy produced by the electrical resistances. More generally, as respiratory activity makes cheese ripening an exothermic process, it would appear possible to avoid some of the heating expenditure and reduce some of the cooling expenditure by exploiting the heat produced by cheese respiration. Consequently, we evaluated the electrical energy expenditure tied to heating and then integrated this as a possible potential energy saving following a proposed improvement to the experimental ripening room.
Typically, preliminary measurements showed that electrical energy consumption in the room was essentially due to ventilation: when ventilation was on, around of 9 000 W were consumed, and when ventilation was off, electrical energy consumption remained limited to around just 300 W and corresponded to the energy consumption of the pumps circulating the coolant fluid. Consequently, sequential ventilation led to significant savings compared to the continuous ventilation routinely used in ripening rooms. The data from each of the 6 trials performed was used to determine mean electrical energy consumptions and savings (listed in Table 1), leading to the following observations:

- Disconnecting the heating device appeared a significant way to improve the temperature control of the room while reducing electrical energy expenses. Consequently, the expenses tied to cooling energy exactly matched the heat produced by cheese respiration (ignoring the heat lost by the room), and total electrical energy expenditure was cut 16%.
- Sequential ventilation allowed a 49% (SV50) to 61% (SVRT1) reduction in electrical energy consumption.
- When time-based sequential ventilation was performed, the percentage reduction in electrical energy consumption was very close to the percentage of real time where cheeses were ripened without ventilation of the room.
- When temperature-based sequential ventilation was performed, the reduction in electrical energy consumption was close to 60%, exactly matching the reduction obtained during trial SV60.
- The variation in temperature difference between the low and high set-points of the control law applied for monitoring the temperature-based sequential ventilation led to no significantly change in electrical energy consumption.
- During trial SVRT2, a period of sequential ventilation carried out without the two blowing ducts as they were dismantled for cleaning showed a drastic limitation in electrical energy consumption reduction and the gain decreased from 60% to 23%, almost certainly due to poor distribution of cold air inside the ripening room.

Table 1. Savings on electrical energy consumption obtained with sequential ventilation and cutting the heating. CV+H: continuous ventilation with heating; CV-H: continuous ventilation without heating; SV: time-based sequential ventilation; SVRT: temperature-based sequential ventilation; ΔT: temperature difference between the low and high set-points

Trial	Working conditions	Electrical energy consumption (kW/d)	Daily economy (kWh)		Percentage gain (%)	
			H	SV	H	SV
Ref1	CV+H	253	0	0	0	
Ref2	CV-H	212	41	0	16	0
SV50	SV	109	41	103	16	49
SV60	SV	85	41	127	16	60
SVRT1	SV ΔT=1°C	83	41	129	16	61
SVRT2	SV ΔT=0.7°C	87	41	125	16	59
SVRT2	SV ΔT=0.3°C	85	41	127	16	60
SVRT2	SV ΔT=0.3°C without blowing ducts	164	41	48	16	23

In addition to the electrical energy directly consumed by ventilating the room, there was also an 'indirect' electrical energy consumption corresponding to the electrical energy consumed to producing cooling energy. Unlike direct electrical energy consumption, which was accurately measured during each of the 6 trials carried out, indirect electrical energy consumption was not measured. This indirect consumption was thus assessed by cross-comparing all the trials in terms of the mean temperature reached by the glycol-mixture flowing in the cooling circuit supplying the room, and was only calculated for periods during which ventilation was on, with the mean glycol-mixture temperature obtained for the trial Ref1 serving as reference baseline. Assuming a cooling system performance coefficient equal to an annual average of 2.2, then applying this way of calculating to the trials led to an additional daily economy ranging from 12 kW/d (SV50 and SV60) to 19 kW/d (ref2). For the temperature-based sequential ventilation trials, the additional savings were less due to disruptions in air temperature regulation due to the choice of the temperature difference between the low and high set-points. Only the lower difference (0.3°C) led to an additional daily saving (of about 3 kW/d), while the two other differences tested (0.7°C and 1°C) led to additional electrical energy consumption of 7 kW/d and 11 kW/d, respectively. In conclusion, performing cheese ripening under sequential ventilation can, in some cases, make it possible to save additional electrical energy indirectly, but this 'indirect' saving is lower compared to the direct saving described earlier. In the cases giving rise to an increase in electrical energy demand, the additional consumption is also very limited in comparison with the potential savings generated by using sequential ventilation.

Furthermore, we made a rough evaluation of the gain in ripening process productivity. This rough estimate varied from 0.13% when only stopping heating to 0.42% when using sequential air ventilation, thus reaching 0.55% when combining the two reduction strategies.

In conclusion, an improved approach to ripening room monitoring was suggested, which entailed temperature-based sequential ventilation, with a temperature variation ideally ranging from 0.6 to 0.8°C, together with disconnecting the room heating device. The economic impact of the resulting electricity savings culminated at 0.55% of the productivity of the cheese ripening process performed in the ripening room under study.

Evolution in cheese ripening dynamics and final product quality

To compare the evolution in cheese ripening dynamics and final cheese quality as a function of ventilation conditions, we evaluated the main microbiological, biochemical and sensory characteristics of the cheeses.

The 8 most important micro-organisms found in ripened Saint-Nectaire cheese were enumerated on selective media as previously described [1]. Counts were carried out on samples of cheese ripened under the different studied ripening conditions, and cheese core and rind samples were counted separately.

In the cheese core, the concentrations of Gram-negative bacteria, yeast, mould, Gram-positive non-lactic acid bacteria and Leuconostocs did not change during the process, whatever the ventilation conditions. Concentrations of lactic acid bacteria (LAB), Lactobacillus and Enterococcus increased during the same

time. LAB grew between day 1 and day 14, reaching 10^6 to 5 10^7 CFU.g^{-1} before remaining constant after day 14. Under the SVRT2 condition, LAB grew more quickly, reaching 10^8 CFU.g^{-1} at day 7, and then remained constant. Lactobacillus continued to grow throughout the process, reaching about 10^7 CFU.g^{-1} under the studied ripening conditions. Enterococcus count increased a little during ripening, but it is difficult to highlight an effect of the ripening conditions. In fact, the growths measured during the trials with sequential ventilation fell in the range of growth measured during the reference trials, i.e. between Ref1 and Ref2. The difference with Ref1 and Ref2 did not point to any clear effect of ventilation mode, whether continuous or sequential.
In the cheese rind, concentrations of Gram-positive non-lactic acid bacteria and Leuconostocs did not change during the process, whatever the ventilation conditions. All the other strains showed a more or less substantial growth, excluding Enterococcus, which grew continuously over the 28 days, all other strains generally grew during the first 7 or 14 days, with concentrations then remaining stable. Regardless of the ventilation conditions, growths in cheese rind exhibited the same overall changes. It can be globally concluded that ventilation mode has no significant effect on the evolution of Saint-Nectaire cheese strains.

The main biochemical characteristics of cheese, i.e. pH, substrate concentration, and nitrogen fractions, were determined on cheese core and cheese rind samples. In the core, pH showed a low increase whatever the ripening conditions, with final values ranging between 5.2 and 5.5. In the rind, pH increased from 5.2 to final values ranging from 5.7 to 6.7. These differences in final pH cannot be related to ventilation conditions, and are probably due to cheese heterogeneity and flora activity.

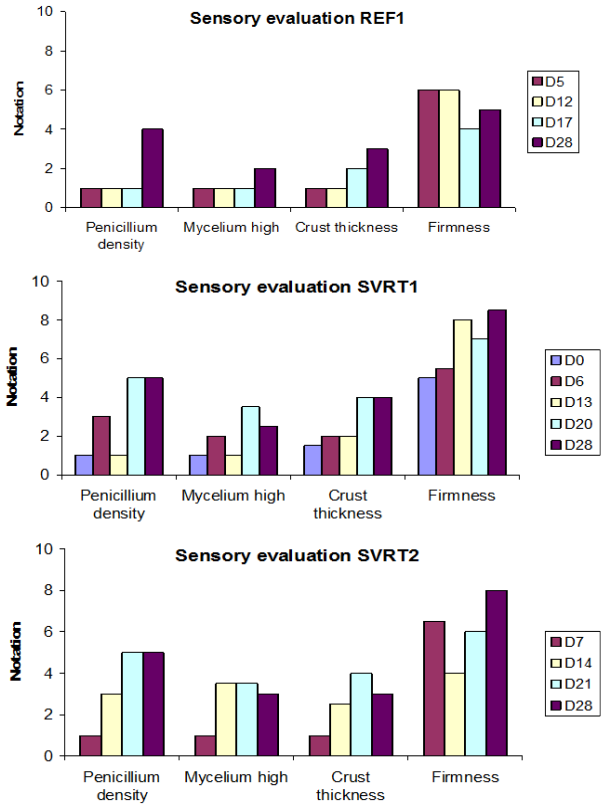

Figure 1. Scores by non-trained experts of the 4 sensory descriptors (scale 0-10) vs. ripening time for trials Ref1, SVRT1 and SVRT2 (D = day of cheese sampling).

Evolutions in sugar and organic acid concentrations were similar between each type of the room ventilation regime. At the beginning of ripening, lactose concentrations were lower than 1 g.kg^{-1} wet cheese in the rind and around 3 g.kg^{-1} in the core. After 14 ripening days, lactose concentrations were still lower than 1 g.kg^{-1} in the core. In the cheese core, galactose concentrations decreased linearly from 5-8 g/kg at the start of ripening to around 2 g.kg^{-1} at the end of ripening. In the cheese rind, galactose concentrations varied over a very large range, from 2 to 9 g.kg^{-1}, but decreased similarly whatever the ventilation conditions. Lactic acid

concentration remained constant in the cheese core at close to 12-14 $g.kg^{-1}$ throughout the ripening process. Cheese rind showed a small decrease in lactic acid concentration versus ripening time, reaching final values of around 5 to 8 $g.kg^{-1}$. Acetic acid concentrations increased linearly from 1.5 $g.kg^{-1}$ to 5 $g.kg^{-1}$, whatever the trials. NH_3 concentrations remained stable during ripening, at just under or over 2 $g.kg^{-1}$ in both cheese core and cheese rind.

Non-trained experts performed a sensory evaluation of the cheeses versus ripening time based on 4 sensory descriptors: Penicillium density, peak Penicillium, crust thickness, and cheese firmness, with a score ranging from 0 to 10. Cheeses were sampled every week, and 5 sensory evaluations were performed over the ripening process. Cheeses only ripened under temperature-based sequential ventilation (SVRT1 and SVRT2) were evaluated and compared to the evaluation a reference trial (Ref1). The results are presented in Figure 1. As a general rule, 3 descriptors showed an increase in score versus ripening time that was modest for peak Penicillium and crust thickness but high for Penicillium density. The fourth descriptor (cheese thickness) scored highest (always higher than 4), but remained relatively constant versus ripening time, except at the end of ripening trials performed with temperature-based sequential ventilation where the scores ranged from 6 to 8, i.e. higher than the score (5) of the trial with continuous ventilation. Consequently, the cheeses obtained under sequential ventilation appeared more firm, but as a general rule, it is possible to conclude that sequential ventilation did not negatively affect the quality of the Saint-Nectaire cheeses ripened under these conditions.
In conclusion, sequential ventilation had no significant effect on cheese quality. Ripening microbial flora, the main biological characteristics of the cheese, and sensory descriptors showed little evolution versus ripening time compared to continuous ventilation.

CONCLUSION

The main conclusions can be summarized as follows:

- Cheese ripening led to significant respiratory activity. This activity was not significantly affected by either continuous or sequential room ventilation procedures. Air renewal and the door opening were identified as the two major factors acting on the amount of CO_2 and O_2 observed in the ripening room.
- Under the conditions of this study, mean savings in electrical energy consumption under temperature-based sequential ventilation at a temperature variation close to 0.7°C reached 125 kWh per day, which translates into a 0.43% increase in ripening room productivity.
- It was proposed to further improve the ripening room by disconnecting the room heating device in order to keep heat production down at the level provided by the cheese respiration activity. This adjustment could increase ripening room productivity by 0.12%.
- Finally, it was shown that sequential ventilation had no significant effect on cheese quality. Ripening microbial flora, the main biological characteristics of the cheese, and sensory descriptors showed little evolution versus ripening time compared to continuous ventilation.

In the future, the cheese industry is encouraged to look at how these results could be generalized to the large number of ripening rooms used for cheese production in Europe. A dual approach can be suggested: first, introducing sequential ventilation, and second, improving and modernizing the ripening room control procedures.

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