THEORETICAL ASPECTS OF COTTON LINT HUMIDIFICATION USING A FOUR-SECTION ULTRASONIC AEROSOL DEVICE BEFORE BALING

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Abstract. This paper presents a theoretical design of an ultrasonic aerosol humidifier for cotton lint before baling. A 1.7 MHz generator supplies humid air to a four-section chamber in which flow alternates between the upper and lower faces of a moving fiber layer. Capillary-wave atomization, droplet evaporation, psychrometric conditioning, and a GAB–LDF cross-flow moisture-transfer model are considered jointly. At an air mass flux of 0.30 kg/(m²·s) and an 8 s residence time, the predicted moisture nonuniformity decreases from 12.7% under one-sided treatment to 4.5% with four sections. The design for a 2.5 t/h line includes a 4.63 m² conditioning area, approximately 4,300 m³/h air supply, and 20 generator modules. These results are model-based design estimates that require prototype validation.

Keywords: cotton lint; ultrasonic aerosol; humidification; alternating cross-flow; GAB isotherm; LDF kinetics; moisture uniformity; baling.

INTRODUCTION

Cotton lint loses moisture during drying, cleaning and pneumatic transport. Very dry lint is susceptible to static charge and increased pressing resistance, while excessive moisture may impair color and storage stability. The investigated target is approximately 6.5–7.5% bale moisture; levels above about 8.0–8.5% require particular caution. Effective conditioning must therefore control both mean moisture gain and its distribution through the fiber layer [1–3].

Conventional spraying can create wet spots, whereas one-sided humid-air supply commonly leaves a gradient between the entry and exit faces. The investigated solution combines ultrasonic production of fine aerosol with a stationary four-section chamber: air passes downward through the lint in odd-numbered sections and upward in even-numbered sections. The aim is to establish the physical models, compare section counts and justify preliminary equipment parameters without assuming that calculated performance has already been verified in an industrial installation.

LITERATURE REVIEW

Research on moisture restoration before baling has demonstrated the trade-off between easier compression and possible loss of stored-fiber quality [1–3]. Cotton moisture measurements also depend on the test method and whether moisture is expressed on a wet or dry mass basis [4, 5]. Studies of ultrasonic atomization

describe how frequency and liquid properties influence droplet size [6]. The design examined here integrates this fine-aerosol source with cross-flow absorption, air psychrometrics and alternating top–bottom distribution, rather than treating ultrasonic atomization alone as a novel effect.

RESEARCH METHODOLOGY

The atomization estimate uses a Lang-type capillary-wave relationship between ultrasound frequency and characteristic droplet diameter: $d = 0.34[8\pi\sigma/(\rho w f^2)]^{(1/3)}$, where σ and ρw are water surface tension and density. At 20 °C, σ = 0.0728 N/m and ρw = 998 kg/m³. The simplified droplet-evaporation law $d^2(t) = d_0^2 - Kt$ gives an estimated lifetime $t_{ev} = d_0^2/K$; K depends on vapor diffusivity and the vapor-density difference between the droplet surface and ambient air. These expressions support initial dimensioning but neglect droplet cooling, local saturation and the full aerosol size distribution [6].

Air preparation is evaluated with humidity ratio $x = 0.622\varphi ps/(p - \varphi ps)$ and moist-air enthalpy $h = 1.006T + x(2501 + 1.86T)$, where φ is relative humidity as a fraction and ps is saturation vapor pressure. Ultrasonic mist evaporation is treated as approximately adiabatic; however, avoidance of condensation also requires the local fiber-surface temperature to remain above the local dew point. Preheating and a droplet separator are therefore included in the proposed system.

Fiber equilibrium moisture is represented by a Guggenheim–Anderson–de Boer (GAB) isotherm, with engineering values Wm = 0.042, C = 10 and K_GAB = 0.78. Short-time absorption is modeled by linear-driving-force (LDF) kinetics, $\partial W/\partial t = k[We(\varphi) - W]$, taking $k = 0.06\ s^{-1}$. The transverse air balance is $g\partial x/\partial \mu = -\partial W/\partial t$, where g is the air mass flux and μ represents depth on a layer-mass coordinate. The numerical study assumes a surface loading of 1.2 kg/m², 40 depth elements and a 0.005 s time step. These input coefficients are assumptions requiring material-specific identification, not independently measured constants.

One-, two-, four- and eight-section configurations are compared for an 8 s passage. Air enters from above in Sections 1 and 3, and from below in Sections 2 and 4. A moving fiber element thus encounters periodic flow reversal without switching valves; for n sections, the effective interval is τ/n. Performance is characterized by average moisture gain, peak local moisture and the depth-wise coefficient of variation (CV).

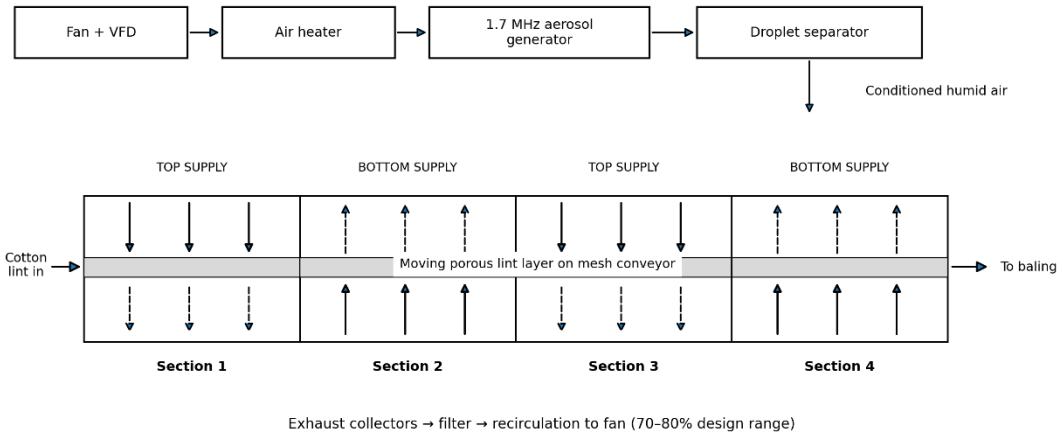
RESULTS AND DISCUSSION

At 1.7 MHz, the capillary-wave estimate gives 2.9 μm droplets, versus approximately 2.3 μm at 2.4 MHz. In the simplified evaporation example at 25 °C and 90% relative humidity, a nominal 3 μm droplet evaporates in about 0.0195 s; a 50 μm droplet requires approximately 5.43 s. The selected 1.7 MHz frequency balances expected fineness, transducer service conditions and industrial availability. These computed lifetimes should not be interpreted as evidence that every droplet evaporates before encountering lint.

For outside air at 25 °C and 40% relative humidity, preheating to 50 °C followed by adiabatic humidification to 95% relative humidity yields a calculated outlet temperature of 24.3 °C and moisture addition of 10.31 g/kg dry air. Without preheating, the corresponding values are 16.6 °C and 3.37 g/kg. The proposed

humid-air working range is about 25–30 °C at 92–95% relative humidity; local dew-point conditions still require verification.

Figure 1. Structure of the four-section alternating cross-flow humidifier.



The fan supplies air through a heater, ultrasonic generator and droplet separator to fixed upper and lower collectors (Figure 1). Opposite-side collectors extract the air for filtration and recirculation. The alternating flow makes both faces of the moving lint layer receive the high-vapor-content supply in successive sections. Computed effects of section count are summarized in Table 1.

Table 1. Calculated effect of airflow direction and section count (τ = 8 s; T = 30 °C).

Air flux, kg/(m²·s)	Sections	Moisture gain, pp	CV, %	Maximum moisture, %
0.30	1	1.91	12.7	8.88
0.30	2	1.87	4.6	7.43
0.30	4	1.87	4.5	7.36
0.30	8	1.87	4.5	7.33
0.45	1	2.29	11.0	8.88
0.45	2	2.25	3.4	7.59
0.45	4	2.25	3.3	7.54
0.45	8	2.25	3.3	7.51

At g = 0.30 kg/(m²·s), four alternating sections lower the modeled CV from 12.7% to 4.5% while maintaining a similar average moisture gain (1.91 versus 1.87 percentage points). The predicted maximum local moisture decreases from 8.88% to 7.36%. At g = 0.45 kg/(m²·s), the CV falls from 11.0% to 3.3%. Increasing the count from four to eight gives no meaningful further CV improvement in these calculations, making four sections a rational compromise between uniformity, collector complexity and airflow leakage.

For a 2.5 t/h cotton-lint line, the design adopts a 1.85 × 2.5 m conditioning zone (4.63 m²), divided into four sections of 0.625 m. The air supply is approximately 4,300 m³/h; total estimated pressure loss is 847 Pa, including about 107 Pa across the fiber layer. A 2.2 kW radial fan and a 0.37 kW conveyor drive are selected. The aerosol system contains 20 modules with 10 transducers each (200 total). Sixteen operating modules deliver a nominal 56 kg/h of mist using about 4.8 kW, while four reserve modules allow approximately 70 kg/h at 6.0 kW. Proposed

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transducer water depth is 25–45 mm; cooling-water heat recovery can assist inlet-air preheating.

The findings remain subject to model limitations. Near saturation, evaporation slows; real aerosols may exhibit deposition, coalescence and condensate formation. The adopted GAB–LDF constants, lint density and air distribution have not been independently calibrated for every cotton batch. Wet-basis product moisture must be distinguished from dry-basis sorption moisture. A prototype study should measure droplet-size distributions, generator and absorbed water masses, drainage, the upper–middle–lower moisture profile, pressure loss and bale quality after storage. Accordingly, the four-section choice is a model-based design recommendation rather than a universal experimentally verified optimum.

CONCLUSION

A continuous ultrasonic humidifier with four stationary alternating-flow sections is proposed for pre-baling cotton-lint conditioning. The 1.7 MHz atomization model predicts a 2.9 μm characteristic droplet diameter; the associated evaporation estimate requires experimental checking at high humidity. The GAB–LDF cross-flow calculations show a reduction in moisture CV from 12.7% to 4.5% at $g = 0.30$ kg/(m²·s) and $\tau = 8$ s, without a substantial loss of moisture gain. For 2.5 t/h throughput, the design provides a 4.63 m² treatment area, roughly 4,300 m³/h air supply and 20 aerosol-generator modules. The proposed layout and parameters provide a basis for calibrated laboratory and industrial validation.

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