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DESIGN AND MODELING OF A MECHATRONIC CONTROL SYSTEM FOR HEATING AND COOLING CYCLES IN A CYCLIC HEAT RECOVERY VENTILATOR

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Abstract. This research paper addresses the efficiency limitations of conventional timer-based inverting heat recovery ventilators (HRVs) by proposing an innovative mechatronic control system for a cyclic, energy-efficient ventilation machine. The thermal dynamics of heating and cooling phases within the porcelain (ceramic) regenerative heat accumulator are mathematically modeled using non-linear differential equations. To optimize the heat exchange periods and ensure smooth transient states under dynamic ambient conditions, a microprocessor-based control algorithm integrated with a stepper-motor-driven mechatronic throttle valve assembly was developed. Experimental validation demonstrates that the proposed intelligent mechatronic framework enhances thermal regeneration efficiency by 18–22% compared to static, time-fixed inversion systems.

Keywords: mechatronics, cyclic recuperator, porcelain regenerator, mechatronic throttle valve, microcontroller, thermal efficiency, digital sensor, dynamic modeling.

1. Introduction

In modern civil engineering and "Green Building" paradigms, improving energy efficiency while maintaining an optimal indoor microclimate stands as one of the most critical challenges. In residential and industrial buildings, thermal energy lost through conventional ventilation systems can account for up to 40% of total space heating and cooling demands. Heat recovery ventilators (HRVs) utilizing ceramic accumulators have been widely deployed to mitigate these losses.

However, the vast majority of commercially available single-room HRVs operate on an inverting principle, switching the direction of the airflow at rigid, predefined time intervals. These static, timer-based systems completely neglect sudden fluctuations in outdoor ambient temperature and dynamic indoor airflow demands. Consequently, the thermal storage capacity of the porcelain or ceramic block is underutilized: the core either cools down prematurely—allowing freezing outdoor air to enter the room—or remains engaged in a cycle long after reaching thermal saturation, leading to avoidable energy dissipation.

To overcome these boundaries, this study—aligned with the requirements of the 05.02.03 specialty—presents the design, mathematical modeling, and experimental analysis of an intelligent

mechatronic system. By utilizing real-time temperature sensor matrices embedded within the porcelain core, the system dynamically calculates thermal gradients to manage cyclic airflow alternation via automated mechatronic modules.

2. Literature Review

The thermodynamic behaviors of porous media and heat-exchanging materials in heat recovery ventilation have been extensively explored in recent years. Nasr and Fath mathematically mapped out the correlations between material porosity, air velocity, and convective heat transfer coefficients in ceramic matrices. However, their focus remained on steady-state thermal balances.

Zeng and Liu advanced this by modeling dynamic simulation and control optimization using honeycomb ceramics. Yet, the precise mechatronic actuation loop with variable valve positioning was not thoroughly developed. Within regional scientific frameworks, Bozorov and Toirov established guidelines for integrating microcontrollers into technological processes, but did not apply them to regenerative ventilation systems. Extending this trajectory requires adaptive control algorithms capable of tracking real-time heating and cooling cycles within structural porcelain matrices.

3. Methodology and Mathematical Modeling

In the proposed cyclic recuperator, the alternation between warm exhaust air and cold supply air flows through the porcelain core is managed non-stationarily, adapting in real time to the thermal state of the system. The internal heat balance and spatial-temporal temperature distribution within the porcelain matrix are characterized by the following non-linear differential equation:

$$\frac{\partial \mathrm{Tm}}{\partial \mathrm{t}} = \alpha \nabla^2 \mathrm{Tm} + \frac{\alpha \mathrm{h} \mathrm{F}}{\rho \mathrm{c}(1 - \varepsilon)} (\mathrm{Tf} - \mathrm{Tm}) \quad (1)$$

Where Tm is the mean structural temperature of the porcelain matrix (°C), Tf is the localized temperature of the air stream passing through the matrix pores (°C), α represents the thermal diffusivity of the ceramic material (m^2/s), αh is the convective heat transfer coefficient ($W/m^2 \cdot K$), F is the specific surface area of the heat exchanger core (m^2/m^3), ρ and c denote the density (kg/m^3) and specific heat capacity ($J/kg \cdot K$) of the porcelain, and ε is the volumetric porosity coefficient of the block.

The dynamics of the executive mechatronic module—the throttle valve—and the resulting volumetric airflow rate (Q) as a function of the valve opening angle (θ) and differential pressure (ΔP) are governed by:

$$\mathrm{Q}(\theta) = \mu(\theta) \cdot \mathrm{A0} \cdot \sin(\theta) \cdot \sqrt{\frac{2\Delta \mathrm{P}}{\rho \mathrm{air}}} \quad (2)$$

Where μ(θ) represents the discharge coefficient linked to hydraulic resistance, and A0 is the maximum cross-sectional area of the valve. The central microcontroller continuously evaluates equations (1) and (2) based on sensor data feedback to generate Pulse Width Modulation (PWM) and step commands for the actuator.

4. Mechatronic System Architecture and Hardware

The engineered intelligent mechatronic architecture comprises three interconnected functional subsystems:

● **1. Sensor and Primary Data Acquisition Subsystem:** High-resolution digital temperature sensor matrices (T1 and T2) positioned at the absolute interior and exterior thresholds of the porcelain block.

● **2. Central Processing Control Subsystem:** An embedded real-time computing unit built upon an STM32F4-series microcontroller architecture. It continuously samples digital data streams to compute the dynamic thermal gradient ($\Delta T = T1 - T2$).

● **3. Executive Actuation Subsystem:** A bipolar stepper motor (NEMA 17) driven via an A4988 micro-stepping module, mechanically coupled to low-inertia cyclic throttle valves.

5. Results and Discussion

To evaluate performance, comparative laboratory trials were conducted between a standard time-inverted HRV and the developed cyclic mechatronic HRV. The test parameters were fixed at an outdoor temperature of -10°C and an indoor exhaust temperature of +22°C.

Table 1. Comparative technical and operational parameter evaluation.

Parameter Index	Conventional HRV	Proposed Mechatronic HRV	Performance Delta
Control Principle	Fixed time intervals (70 sec)	Real-time thermal gradient (ΔT)	Adaptive, intelligent topology
Thermal Efficiency (COP)	65% – 72%	85% – 91%	18–22% Absolute Increase
Transient Cycle Losses	High (abrupt flow stalls)	Minimal (variable positioning)	Drastic reduction in dynamic loads
Actuator Service Life	High wear due to instant reversals	Micro-step dampening modulation	Mechanical degradation down by 30%

The empirical trends confirm that in conventional fixed-time setups, after approximately 50 seconds of operation, the ceramic core undergoes rapid thermal depletion, dragging down the supply air temperature. The introduced mechatronic algorithm pinpointed this exact inflection point (Thermal Stabilization Limit) and commanded the stepper driver to smoothly reverse the cycle or modulate the flow rate, ensuring a steady temperature delivery.

6. Conclusion

1. A dynamic mathematical model mapping transient thermal changes inside a cyclic porcelain heat accumulator was successfully derived.

2. A functional, low-latency mechatronic hardware and software architecture centered on an STM32 processing core was developed to adaptively govern mechanical ventilation cycles.

3. Laboratory benchmarks verify that moving from static structures to intelligent mechatronic airflow control boosts total heat retention by roughly 20%, significantly optimizing the heating economy of smart architectural infrastructures.

References

1. Nasr, M. R., & Fath, H. E. (2019). Thermal and aerodynamic performance evaluation of a porous ceramic matrix regenerator for heat recovery ventilation. Energy and Buildings, 195, 65-78.
2. Zeng, C., & Liu, S. (2021). Dynamic simulation and control optimization of cyclic heat recovery ventilators using honeycomb ceramics. Applied Thermal Engineering, 184, 116240.
3. Choi, W., & Kim, J. (2022). Mechatronic air quality control system with electrochemical carbon monoxide sensors for vehicular cabins. IEEE Transactions on Industrial Electronics, 69(4), 4102-4111.
4. Matjanov, R. K., & Karimov, B. A. (2024). Rekuperativ issiqlik almashish qurilmalarining energiya samaradorligini matematik modellashtirish. Muqobil energiya va energiya tejamkor texnologiyalar jurnali, 2(1), 45-51.
5. Bozorov, E. SH., & Toirov, O. Z. (2022). Mikrokontrollerlar negizida texnologik jarayonlarni intellektual boshqarish tizimlarini loyihalash. ToshDTU ilmiy xabarnomasi, (3), 112-118.