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Research on Development and Performance of Intelligent Protective Mask Based on Flexible Heating and Piezoresistive Sensing Technology

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Abstract: Aiming at the problems of worsening air pollution and the single function of traditional masks, this paper develops an intelligent mask integrating heating disinfection and respiratory monitoring. A copper wire heating layer is fabricated by hot pressing on a non-woven lining and combined with a sensing film to realize the integration of temperature regulation and respiratory monitoring. The results show that the mask can rise to 60 °C within 50 s and reach 72 °C in 200 s, with stable multi-level temperature control at 30 °C, 40 °C, and 70 °C. It can effectively identify different breathing patterns: the resistance change rate of normal breathing is 5–10%, deep breathing is 20–30%, and shallow breathing is 2–5%. The peak value exceeds 30% after exercise and returns to the baseline within 3–5 s, showing excellent respiratory recognition ability. This research provides a new idea for the development of intelligent protective equipment integrating environmental adaptability and health monitoring.

Keywords: Flexible heating; Flexible piezoresistive sensor; Intelligent mask; Respiratory monitoring

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1. Introduction

Traditional protective masks mainly block airborne particulate matter and droplets through filtration and physical barrier functions, playing an important role in preventing the spread of respiratory infectious diseases. However, traditional masks have limitations such as limited protection capacity, high breathing resistance, poor wearing comfort for long-term use, and non-reusability [1–4]. With the development of intelligent technology, intelligent masks have become a research hotspot [5–8]. Domestic institutions and Xiamen University, including Xiaomi, Shanghai Yuantian Electronic Technology Co., Ltd., and Xiamen University, have taken the lead in developing intelligent masks with respiratory monitoring and physiological data analysis functions. Nevertheless, existing intelligent masks still suffer from a single function and low reusability.

The core technology of flexible heating clothing elements lies in hot-press bonding. Copper wires are arranged in a specific circuit on non-woven fabrics and bonded by hot pressing to form flexible heating liners. Such materials possess excellent electrothermal, thermal, and mechanical properties as well as temperature control performance, which can flexibly adjust heating output according to actual demands and maintain structural integrity and functionality during long-term service [9–11]. Flexible piezoresistive sensors are prepared by the solution-blending method. Modified graphite/polyurethane (MGT/PU) composite films exhibit good electrical conductivity, mechanical performance, and sensitivity, suitable for wearable health monitoring systems to collect real-time physiological signals such as pulse and blood pressure [12–17].

In view of the increasingly severe air pollution and the single function of conventional masks, this study develops an intelligent protective mask with self-cleaning, health monitoring, and comfort improvement functions by combining flexible heating and piezoresistive sensing technologies [18–20]. The mask not only meets the high-efficiency protection needs in special environments, but also provides personalized temperature regulation and health status monitoring for users, greatly improving wearing comfort and service safety.

2. Experimental materials and methods

2.1. Experimental materials and instruments

2.1.1. Main materials

0.1 mm red copper wire (Quanzhou Jiadai New Material Co., Ltd.); 20 g/m^2 non-woven fabric (Guangzhou Nanqixing Non-woven Fabric Co., Ltd.); adhesive interlining (Erqi District Yongzhuo Garment Accessories Store, Zhengzhou); CNT/PU composite film.

2.1.2. Experimental equipment

Self-developed fabric thermal performance testing system, consisting of infrared camera (TP-8, Wuhan Guide Infrared Co., Ltd.), Agilent multimeter, DC regulated power supply and infrared image acquisition software; the infrared camera has a resolution of 384 × 288 pixels with a shooting distance of 30 cm from the sample platform; flexible sensor performance detection system; digital dual-display multimeter (U3402A, Agilent, USA).

2.2. Preparation of flexible heating non-woven functional layer

Copper wires are arranged along marked routes and carefully placed on non-woven fabric. A small amount of glue is dipped with a toothpick and applied to the fixing positions to paste copper wires onto the mask. Longitudinal copper wire circuits are arranged on both sides to reserve space for the nasal sensing film. Conducting wires are led out from appropriate positions of the copper circuit for power and sensor connection, with copper foil serving as electrode terminals.

2.3. Integrated fabrication of an intelligent protective mask

A flexible pressure sensor layer is constructed based on the pressure difference generated during breathing to explore the response performance for respiratory signal acquisition. The sensing film and copper foil electrodes are arranged on a non-woven lining to fabricate multifunctional piezoresistive sensors.

The functional layer is integrated with a non-woven fabric and a melt-blown layer to assemble the intelligent mask, and its heating circuit and sensor response characteristics are investigated. The heating circuit and strain sensor are arranged at designated positions of medical protective masks to fabricate the intelligent mask (**Figure 1**).

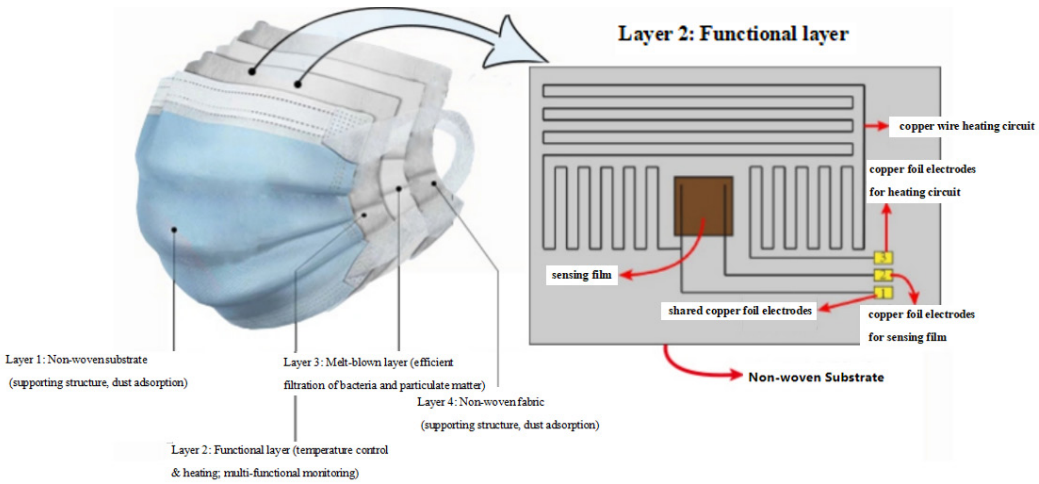

Figure 1. Structure of the intelligent protective mask.

2.4. Performance test of the intelligent protective mask

After integration, the mask is worn simulating the actual wearing state for the heating performance test by the fabric thermal performance tester. Volunteers wear the mask to simulate four breathing states: normal breathing, deep breathing, shallow breathing, and post-exercise heavy breathing. The flexible sensor detection system and digital multimeter are adopted to monitor resistance changes.

3. Results and discussion

3.1. Analysis of heating performance

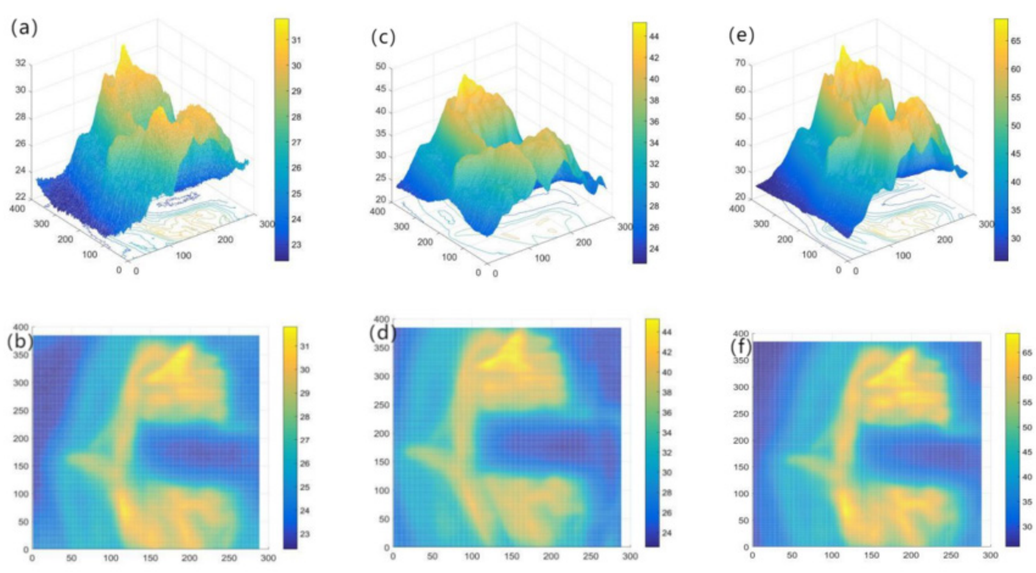

Figure 2. (a-b) 3D infrared thermography and thermal images at first gear; (c-d) 3D infrared thermography and thermal

images at second gear; (e-f) 3D infrared thermography and thermal images at third gear.

When switched to the first gear (green indicator), the maximum temperature reaches about 30 ℃ with an average temperature around 26 ℃, providing a comfortable wearing experience for rhinitis patients. At the second gear (blue indicator), the maximum temperature rises to about 40 ℃, supplying warm inhaled air in cold weather. At the third gear (red indicator), the maximum temperature approaches 70 ℃; continuous heating for 30 min achieves a sterilization effect.

3.2. Respiratory monitoring performance

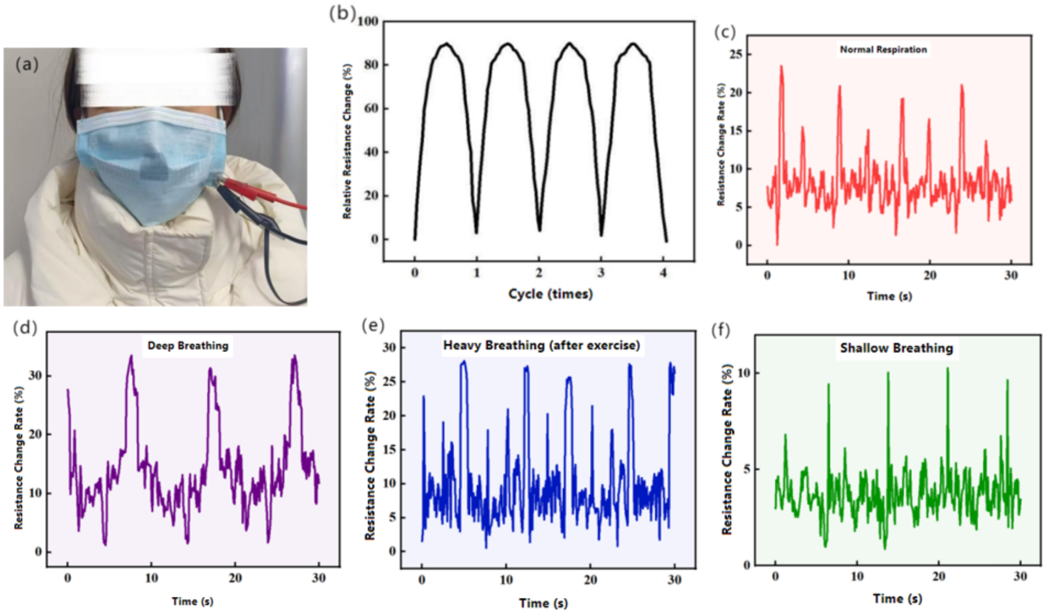

Figure 3. (a) Physical wearing photo; (b) Relative resistance change rate of multiple cycles; (c-f) Resistance change rate under different breathing patterns.

The PU-modified graphite sensor presents typical periodic response characteristics. During normal breathing, resistance rises regularly in inhalation and drops in exhalation, highly consistent with the respiratory rhythm. The excellent conductivity of modified graphite enables sensitive capture of slight thoracic undulation, while the good flexibility of the PU substrate ensures stable sensor performance under regular deformation. The resistance change rate maintains 5–10% under normal breathing with good baseline stability and repeatability.

Under deep breathing, the thoracic expansion increases sensor stretching, extending the conductive path and raising the resistance change rate to 20–30%. The sensor shows fast response (< 0.5 s) and high signal fidelity, effectively distinguishing deep breathing from normal breathing. After strenuous exercise, the respiratory frequency and depth increase; the peak resistance change rate exceeds 30% with a baseline recovery time of 3–5 s. Under shallow breathing, the resistance change rate drops to 2–5% with slight signal fluctuation due to irregular breathing rhythm. The sensor maintains stable signal consistency and repeatability during long-term use, providing reliable technical support for clinical applications of intelligent masks.

4. Conclusion

This study develops an intelligent protective mask integrating flexible heating and piezoresistive sensing, realizing integrated heating disinfection and respiratory monitoring. With a copper wire spacing of 0.5 cm and an applied voltage of 8 V, the fabric temperature rises to 60 ℃ within 50 s and reaches 72 ℃ in 200 s. Steady temperature control at 30 ℃, 40 ℃, and sterilization.70 ℃ is achieved via three gears, meeting the demands of warmth, comfort, and sterilization. The flexible piezoresistive sensor exhibits high sensitivity and recognition capability: resistance change rate is 5–10% for normal breathing, 20–30% for deep breathing, and 2–5% for shallow breathing; the peak value exceeds 30% after exercise with baseline recovery within 3–5 s, realizing effective identification of various breathing patterns. The intelligent mask shows stable heating response and respiratory recognition performance, possessing broad application prospects.

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Disclosure statement

The authors declare no conflict of interest.

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