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HYBRID SMOKE–TEMPERATURE SENSING FOR ADAPTIVE DUAL-SPEED EXHAUST FAN CONTROL AND MOTOR PROTECTION IN BIOMASS-FIRED SME KITCHENS

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ABSTRACT

Biomass-fired cooking activities in small and medium-sized food enterprises (SMEs) generate smoke and excessive heat that can affect worker comfort, indoor air quality, and production efficiency. Conventional exhaust fan systems are commonly operated manually or at a fixed speed, which may result in delayed smoke removal and unnecessary electrical energy consumption. This study develops an Internet of Things (IoT)-based adaptive dual-speed exhaust fan control and motor protection system using an MQ-2 smoke sensor, DS18B20 temperature sensor, ESP32 microcontroller, and PZEM-004T electrical monitoring module. The proposed control strategy combines smoke-based activation during ignition and high-emission conditions with temperature-based ventilation retention during the cooling stage. The system also incorporates overload and overcurrent protection to improve motor operational safety. Experimental testing showed that the MQ-2 sensor activated the exhaust fan with an average response time of 0.6 s, while the transition from Speed 1 to Speed 2 required approximately 0.8 s when smoke concentration exceeded 1000 ppm. The DS18B20 achieved a temperature measurement accuracy of 97.97% compared with a thermocouple reference. The automatic dual-speed mode produced an average power demand of approximately 25.27 W, compared with 32.07 W for manual operation, corresponding to an average reduction of approximately 21.2%. The motor protection system detected abnormal current conditions and automatically disconnected the exhaust fan during sustained overcurrent conditions. The proposed system integrates adaptive environmental control, energy monitoring, and motor protection into a single IoT-based ventilation platform for biomass-fired SME kitchens.

INTRODUCTION

Indoor air quality is an important consideration in small-scale food production activities that use biomass fuels such as firewood. Combustion processes generate smoke, suspended particles, and excess heat around the cooking area. Prolonged exposure to these conditions may reduce workplace comfort and potentially affect worker health and production efficiency (Irfani et al., 2025; Naibaho & Ramadhan, 2025; Shidqi, 2022). In biomass-fired SME kitchens, ventilation is therefore required not only to remove smoke but also to control excessive heat generated during cooking activities.

Exhaust fans are commonly used as a practical ventilation solution because they can remove contaminated and heated air from the cooking area. However, conventional exhaust fan operation in small-scale food enterprises is frequently performed manually or continuously at a fixed operating condition. Manual operation may cause delayed

ventilation when combustion begins, while continuous operation may consume electrical energy even when the ventilation requirement is relatively low (Irfani et al., 2025), (Yudha et al., 2023). An adaptive control system that responds to actual combustion conditions can therefore provide a more appropriate operating strategy.

The development of microcontroller-based and Internet of Things (IoT) systems has enabled environmental parameters to be monitored and used as control inputs. ESP32-based systems have been applied for environmental monitoring and automatic control because the microcontroller can process sensor data and communicate operational information through a network (Yulianto, n.d.). Smoke sensors such as MQ-2 can be used to identify the presence of combustion-related emissions, while temperature sensors can provide additional information about thermal conditions around the cooking area (Laili et al., 2022; Setia et al., 2025).

Previous exhaust fan control approaches have generally focused on automatic smoke extraction or environmental monitoring. However, simple on/off control does not necessarily address different stages of biomass combustion. During ignition, smoke may appear before the surrounding temperature becomes sufficiently high. Conversely, during the cooling stage, smoke concentration may decrease while residual heat remains around the cooking area. Consequently, relying on only one environmental parameter may cause ventilation to start too late or stop prematurely.

The integration of electrical monitoring provides another important consideration. Exhaust fan motors operate under changing electrical loads, and abnormal current conditions may indicate overload or overcurrent conditions. Continuous operation under abnormal electrical loading can increase motor thermal stress and potentially accelerate motor degradation (Puspita & Darmawan, 2023). Electrical monitoring using the PZEM-004T module can provide voltage, current, and power information for energy analysis and fault detection (Affandi, 2025).

Based on these considerations, a hybrid control approach can combine smoke concentration and temperature as complementary control parameters. Smoke detection can be used to initiate ventilation during ignition and high-emission conditions, while temperature detection can maintain ventilation when residual heat remains around the cooking area. The use of two operating speeds further enables the exhaust fan capacity to be adjusted according to the severity of the combustion condition rather than operating continuously at maximum capacity.

This study therefore develops an IoT-based adaptive dual-speed exhaust fan control system integrated with electrical monitoring and motor protection for biomass-fired SME kitchens. The proposed system uses an MQ-2 sensor to detect smoke concentration, a DS18B20 sensor to monitor temperature, an ESP32 as the main controller, and a PZEM-004T module to monitor electrical parameters. The objectives of this study are to develop a hybrid smoke–temperature control strategy, evaluate the response performance of the exhaust fan under different combustion conditions, analyze the electrical energy consumption of manual and automatic operating modes, and evaluate the performance of the integrated motor protection mechanism.

RESEARCH METHOD

The research method comprises system architecture, ventilation requirement analysis, control strategy, motor protection, IoT monitoring, and experimental evaluation. The system was developed to respond to combustion conditions while simultaneously recording electrical and environmental parameters.

1. System Architecture

The proposed system consists of an ESP32 microcontroller, MQ-2 smoke sensor, DS18B20 temperature sensor, PZEM-004T electrical monitoring module, relay driver, dual-speed exhaust fan, ThingSpeak IoT platform, and MicroSD storage. The MQ-2 sensor is positioned around the furnace area to detect smoke generated during biomass combustion, while the DS18B20 monitors temperature around the cooking area. The ESP32 processes sensor readings and determines the exhaust fan operating mode. The PZEM-004T continuously measures voltage, current, and power consumption. Data are transmitted to ThingSpeak and simultaneously stored on MicroSD as a local backup.

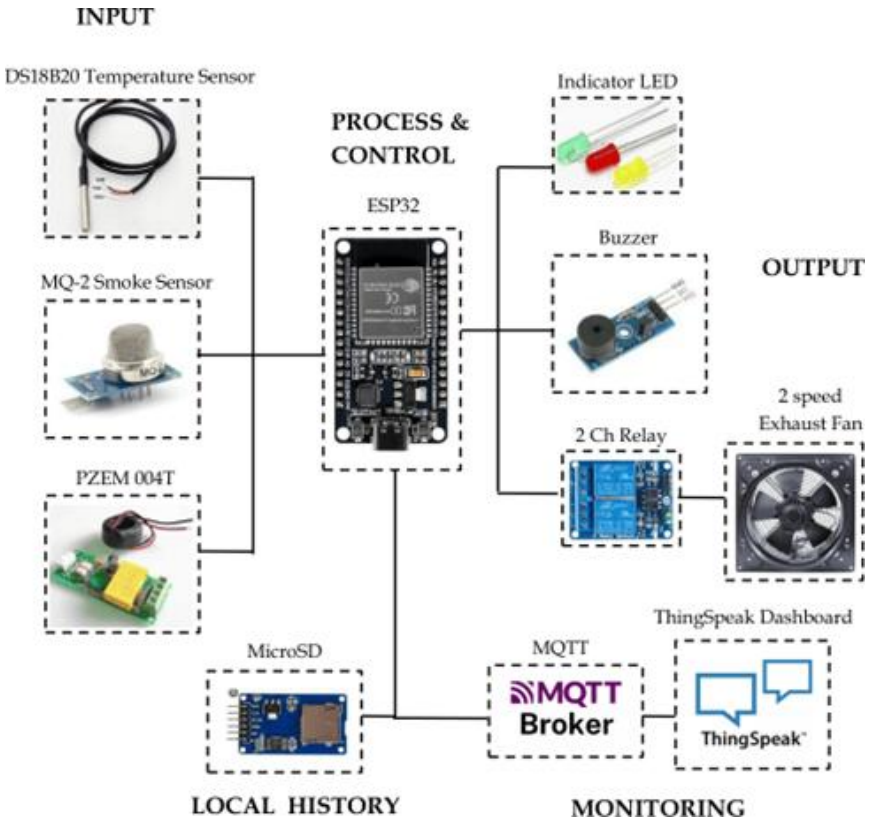


Figure 1. Block Diagram Design of the Device



Figure 2. Final Design of the Device

2. Ventilation Requirement

The production room has dimensions of 3 m × 3 m × 2.5 m, resulting in a volume of 22.5 m^3. The air circulation rate was set at 30 air changes per hour (ACH). The required airflow was calculated as $Q = V \times ACH = 22.5 \times 30 = 675$ m^3/h. An exhaust fan with a measured airflow capacity of approximately 696 m^3/h was selected to meet the calculated minimum requirement.

3. Hybrid Smoke–Temperature Control Strategy

The control system operates through four combustion-related conditions. During ignition, smoke concentration above 100 ppm activates Speed 1. During stable combustion, a temperature above 40°C maintains Speed 1 even when smoke concentration decreases. During high-emission conditions, smoke concentration above 1000 ppm changes the exhaust fan from Speed 1 to Speed 2. During cooling, ventilation remains active while the measured temperature is above 40°C and the smoke-based activation conditions are no longer dominant.

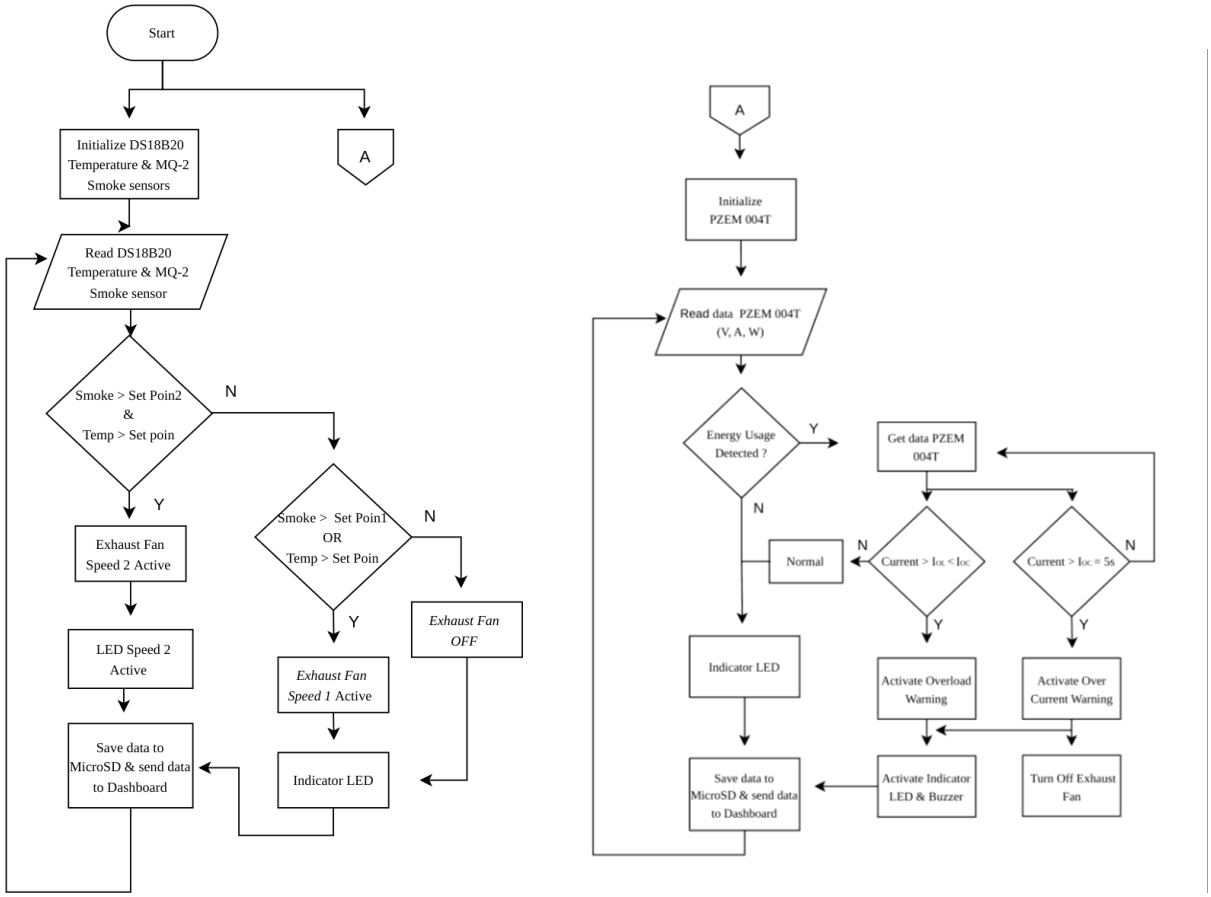


Figure 3 .Functional Block Diagram of the Exhaust Fan Control

4. Motor Fault Detection and Protection

Current monitoring from the PZEM-004T is used to identify abnormal motor operation. When current exceeds the overload threshold but remains below the overcurrent threshold, visual and audible warnings are activated. When current exceeds the critical overcurrent threshold for the programmed sustained period, the ESP32 commands the relay to disconnect the exhaust fan power supply. The sustained-condition delay is intended to reduce false trips caused by temporary current fluctuations or starting current.

5. IoT Monitoring and Data Logging

The ESP32 transmits smoke concentration, temperature, voltage, current, power consumption, and system status to ThingSpeak. The same operational information is recorded on MicroSD as a local backup to reduce data loss during network interruption.

6. Experimental Procedure and Data Analysis

The MQ-2 response was evaluated during biomass ignition and during the transition to Speed 2 when smoke exceeded the second threshold. DS18B20 temperature measurements were compared with a thermocouple reference. Ventilation energy performance was evaluated using manual, automatic single-speed, and automatic dual-speed modes. Motor protection was evaluated under simulated overload and overcurrent conditions. The analysis focused on response time, temperature measurement accuracy, average power demand, and protection response time.

RESULTS AND DISCUSSION

1. Smoke and Temperature Response Performance

The MQ-2 sensor successfully detected smoke generated during biomass ignition. When the smoke concentration exceeded the first threshold, the exhaust fan was activated at Speed 1. The average response time for fan activation was approximately 0.6 s. When smoke concentration exceeded 1000 ppm, the controller changed the exhaust fan from Speed 1 to Speed 2 with an average transition response of approximately 0.8 s.

The DS18B20 successfully maintained exhaust fan operation when the furnace temperature remained above 40°C. This temperature-based control is important during the cooling stage because smoke concentration may decrease before residual heat has been sufficiently removed. The DS18B20 achieved a temperature measurement accuracy of 97.97% compared with the thermocouple reference. The source data also report an average response of approximately 0.5 s for the temperature-based Speed 1 locking mechanism.

2. Comparison of Ventilation Operating Modes

Three exhaust fan operating modes were evaluated: manual operation, automatic single-speed operation, and automatic dual-speed operation.

Experiment	Operating Mode	Duration	Average Power (W)	Total Energy (Wh)
1	Manual	2 h 6 min	31.57	66.30
1	Auto 1-speed	2 h 51 min	31.25	89.06
1	Auto 2-speed	3 h 26 min	25.49	87.43
2	Manual	2 h 41 min	32.57	87.29
2	Auto 1-speed	2 h 43 min	30.31	82.44
2	Auto 2-speed	3 h 55 min	25.04	98.16

Table 1. Comparison of ventilation operating modes

The automatic dual-speed mode produced the lowest average power demand in both experiments. The reported overall average power values were approximately 32.07 W for manual operation, 30.78 W for automatic single-speed operation, and 25.27 W for automatic dual-speed operation. The reported average reduction was approximately 6.80 W (21.2%) compared with manual operation and 5.51 W (17.9%) compared with

automatic single-speed operation. Automatic single-speed operation provided only approximately 1.29 W (4.0%) reduction compared with manual operation.

Because the cooking cycles had different durations, total energy values in Table 1 should not be used alone to compare operating efficiency. Average power demand provides a more consistent basis for comparing electrical loading. The lower average power of the automatic dual-speed mode indicates that adaptive operation can reduce unnecessary electrical loading by allowing the exhaust fan to operate at different speeds according to the detected environmental condition.

3. Motor Protection Performance

The motor protection subsystem was evaluated under simulated overload and overcurrent conditions. The current monitoring subsystem produced an average measurement error of 1.39% during fault detection tests. Under overload conditions, visual and audible warning indicators were activated approximately 1 s after abnormal current detection. Under sustained overcurrent conditions, the controller automatically disconnected the exhaust fan through the relay module. The average cutoff response was approximately 5.75 s, with recorded responses ranging from 5 to 6 s. This response corresponds to the programmed 5-second observation period and provides a safety margin against unnecessary disconnection caused by temporary current spikes or motor starting current.

4. Integrated System Performance

The proposed system integrates environmental-based ventilation control, electrical energy monitoring, IoT supervision, and motor protection. Smoke-based control provides rapid activation during ignition and high-emission conditions, while temperature-based control maintains ventilation when residual heat remains around the cooking area. Adaptive dual-speed operation avoids continuous operation at the same speed. The electrical monitoring subsystem supplies voltage, current, and power information, while the protection mechanism responds to abnormal current conditions. ThingSpeak provides remote observation and MicroSD provides local data backup.

CONCLUSION

An IoT-based adaptive dual-speed exhaust fan control and motor protection system was developed for biomass-fired SME kitchens using hybrid smoke–temperature sensing. The MQ-2 sensor detected smoke during ignition and high-emission conditions, while the DS18B20 maintained ventilation when residual heat remained around the cooking area. Experimental testing showed an average MQ-2 response time of approximately 0.6 s for fan activation and 0.8 s for transition from Speed 1 to Speed 2. The DS18B20 achieved 97.97% temperature measurement accuracy compared with a thermocouple reference.

The automatic dual-speed strategy produced the lowest reported average power demand, approximately 25.27 W, compared with approximately 32.07 W for manual

operation. The reported average reduction was approximately 21.2% compared with manual operation and 17.9% compared with automatic single-speed operation. The motor protection subsystem achieved an average current measurement error of 1.39% and automatically disconnected the exhaust fan under sustained overcurrent conditions with an average response of approximately 5.75 s. Overall, the proposed system combines adaptive ventilation, electrical monitoring, IoT-based supervision, and motor protection in a unified platform for biomass-fired SME food production environments.

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