International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
https://www.theaspd.com/ijes.php

Arduino-Based Fire Exposure Simulation System For Thermo-Structural Evaluation Of Concrete Blocks

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Abstract
This study presents a smart, sensor-integrated fire exposure simulation system, meticulously designed around the Arduino Mega 2560 platform, to evaluate the thermal and structural resilience of concrete and mortar materials under severe fire conditions. The system is engineered in compliance with Indian and international fire testing standards such as IS 3809:1979, IS 1641:1960, IS 1642:1989, ASTM E119, and ISO 834. The heart of the hardware configuration is the Arduino Mega 2560, selected for its high input/output pin count, sufficient memory space, and compatibility with various analogue and digital sensors. Each sensor is chosen based on performance, reliability, and compatibility with real-time data acquisition. Type-K thermocouples are used to monitor internal concrete temperature gradients up to 1200°C. IR/UV flame sensors ensure burner activity is continuously tracked, while MQ-series sensors detect combustible gas leaks, ensuring safety during simulation. The MPX5700 pressure sensor monitors gas line pressure to detect malfunctions, and the max6675 Thermocouple module IR sensor captures non-contact surface temperatures of the test specimens. Real-time sensor data is displayed through a serial interface and LED module, and provisions have been made for data logging and future cloud-based remote monitoring through IoT integrations. The entire system logic was simulated in Proteus software, and the operational sequences were validated using physical experiments. Simulated results and hardware tests confirmed the successful triggering of actuators and alerts based on sensor outputs. The proposed automated fire exposure simulation system bridges the gap between cost-effective hardware and high-standard fire resilience testing. It contributes significantly to the evolution of smarter and safer civil infrastructure while promoting innovation in engineering education and disaster mitigation research

Keywords: *Automated Fire Exposure Simulation System, Type-K thermocouples-series gas sensors, etc.*

1. INTRODUCTION

The growing demand for affordable, inexpensive fire testing equipment in areas with restricted access to conventional laboratory-scale fire resistant chambers is what spurred this investigation. Conventional fire testing infrastructure, although accurate, is costly to operate, administratively restrictive, and inappropriate for small-scale or scattered testing environments. By providing a low-cost, modular, and replicable substitute, the AFESS enables small labs, infrastructure development organizations, and academic researchers to conduct accurate fire exposure assessments without sacrificing data fidelity or standardization. Fire exposure testing is crucial in civil and structural engineering to understand the deterioration behavior of construction materials under thermal load. Traditional fire testing chambers are often bulky, expensive, and offer limited data acquisition features.

2. LITERATURE REVIEW

Real-time monitoring of temperature and moisture parameters in mortars begins at the start of the setting process, which is critical for controlling the execution process in restoration works. Furthermore, it has been observed that lime mortars using recycled aggregate exhibit good technical performance for use in rehabilitation works, albeit without the physical and mechanical features of conventional mortars[1].Builders and architects are

hankering for safer and sustainable alternatives to concrete that do not compromise with their design intent or fire safety requirements[2].
The concrete's residual compressive strength following a specified period of exposure to high temperatures can also be used to characterize its fire resistance. The fire rating of up to four hours is defined in Table 3.4 of BS 8110 part 1 (1997)[3].

It is possible to identify two zones. According to www.besix.com, the regular zone is fire-resistant for one hour, while the safe zone is fire-resistant for two hours. The ability of a structural member to withstand being subjected to a fire without losing its capacity to support loads or to serve as a barrier to stop a fire from propagating is known as fire Resistance [4]. In the event of a fire, structures must be arranged to guarantee their safety and provide users adequate time to flee or seek help (www.besix.com). Our understanding of the behavior of real building fires and their relationship to routine and experimental fire tests has advanced in recent years. An Arduino-based framework for monitoring lime mortars' temperature and moisture in real time is shown in the study. This inexpensive system supports highly precise data collection for façade rehabilitation applications. The critical role of sensors in tracking deterioration and confirming restoration plans in concrete structures is emphasized[5].

2.1Gaps in the Literature

In this research paper, an Automated Fire Exposure Simulation System (AFESS) based on an Arduino Mega 2560 is designed, simulated, and experimentally validated to assess the thermal and structural resilience of cementitious materials, such as mortar and concrete, under high temperature conditions. The created AFESS closes the gap between affordable research infrastructure and conventional fire testing techniques, making a substantial contribution to material science, fire safety engineering, and the creation of civil infrastructure that is resistant to fire. It opens the door for innovation in intelligent disaster-resilient construction technologies and provides engineers and researchers with a strong tool for assessing thermo-mechanical performance. It also guarantees compliance with national and international safety standards.

2.1.1 Significance and Contribution

Compared to commercial fire testing rigs, this system is more than 60% less expensive, allows real-time diagnostics, and reduces the need for user intervention through automatic safety responses. It is appropriate for R&D facilities, educational institutions, and on-site construction testing due to its expandable architecture. The platform can be expanded to test steel reinforcements, polymer composites, coatings, and building panels under fire load in addition to cementitious materials' fire resistance. Its simulation accuracy and material classification performance can be further improved by integrating AI-based models with extra environmental sensors (smoke, humidity).

3. METHODOLOGY

Proteus software was initially used to model the system's operating logic, confirming response sequencing and sensor-actuator interactions. 100 mm concrete cubes and 160×40×40 mm mortar prisms cast by IS 516:1959[6] specifications were subjected to physical testing as per the codal reference mentioned in Table .3. According to the ISO 834 [7]time-temperature curve, these specimens were heated under controlled conditions until they reached 1000°C at a rate of 10°C per minute. LED indicators, buzzer alarms, and OLED display alerts were activated in response to real-time sensor outputs, triggered by events such as gas leaks, flame detection, overpressure, or threshold exceedance. The stage-wise procedure is mentioned in Table 2 and in Figure .2. A serial interface was used to log data, and plans were established for future IoT integration (such as Wi-Fi and LoRa) for remote diagnostics and cloud-based monitoring. The system was designed to replicate standard fire testing environments as prescribed in ASTM E119-20[8] and IS 3809[9]:1979, where temperature, flame exposure, smoke concentration, structural deformation, and load conditions are continuously monitored during the test.

Table 1 Stage-wise Procedure of AFESS

Sl. No	Stage	Inputs	Processing	Outputs
1	Initialization	Arduino boot, gas valve closed	All sensors self-test	Status display, buzzer ready
2	Pre-Test Check	Gas pressure + flame sensor	Verifies safety before ignition	Proceed/Abort
3	Ignition Phase	Flame sensor high, gas on	Relays the fire burner	Confirm burn with the LED
4	Heating Phase	Thermocouple + MAX6675 THERMOCOUPLE MODULE	Compare with the ISO 834 temperature curve[7]	Chamber temperature PID-controlled
5	Monitoring Phase	All sensors	Real-time data collection	Chart plotting, safety alerts
6	Auto-Sorting Trigger	Max temp + surface reading + crack log (manual or ultrasonic sensor in future)	Actuate servo	Direct to bin A/B/C
7	Shutdown Phase	Time reached, error, or manual halt	Close all valves, fan on	Store logs, ready for next test

4. SYSTEM DESIGN

(a) Mechanical Layout & Auto-Sort Mechanism

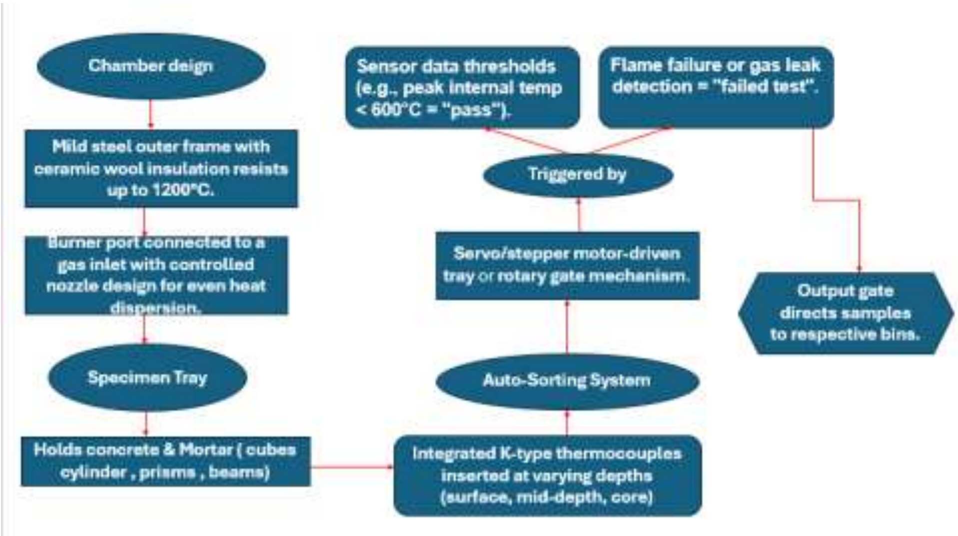

Figure 1 Detailed Layout and Auto-Sort Mechanism on AFESS

(b) Circuit Schematic & Part Integration

SI. No	Module	Arduino Pins Used	Power Supply
1.	Type-K Thermocouple + MAX6675	CS, SCK, SO, GND, VCC	5V
2.	MAX6675 THERMOCOUPLE MODULE (IR sensor)	A4 (SDA), A5 (SCL)	3.3V
3.	MQ-6/MQ-9 Gas Sensor	A0 or D6	5V
4.	Pressure Sensor (BMP280/MPX)	A1 / A2	3.3V or 5V
5.	Flame Sensor (IR/UV)	D7	5V
6.	Servo Motor / Actuator	D9	5V
7.	Display (OLED/I2C)	A4 (SDA), A5 (SCL)	3.3V or 5V

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(c) Sensor Functional Description

The testing system comprised the following sensors and actuators, with their specific purposes detailed in Table 2. In the table below, the sensors' inputs and outputs used in the Proteus simulation are described.

Table 3 Description of Sensor function and its brief description on AFESS

SI. No	Type of Sensor	Functional Description
1.	Type-K Thermocouples	Range: -200° to 1200° C Accuracy: ± 1.5°C at high Temperature Placement: Drilled holes in cube center, embedded using ceramic sealant. Readout Module: MAX6675 (SPI protocol) Calibration: Ice-water bath (0°C) & boiling point (100°C), compared against reference thermometers. Signal Type: Digital (SPI)
2.	MAX6675 Thermocouple Module	Range: -70°C to 380°C (non-contact) Emissivity setting: 0.95 (adjustable) Placement: Outside chamber window; aimed at specimen surface. Use: Validates chamber surface heat rise and simulates human-safe surface detection. Accuracy: ±0.5° Signal Type: Digital
3.	IR/UV Flame Detector	Role: Confirms burner ignition and continuity. Output: Digital HIGH = flame present, LOW = no flame. Trigger: Used in safety logic (burner shutoff if no flame within 2 seconds) Signal Type: Digital.
4.	MQ-6 / MQ-9 Gas Sensors (simulated via POT HG)	Sensed gases: LPG, CO, methane Working voltage: 5V analogue output Calibration: Pre-test baseline reading with no leakage; alarm threshold ≈ 200 ppm for LPG Placement: Near the burner and near the chamber base to detect leakage. Signal Type: Analog
5.	Pressure Sensor (BMP280/MPX) (simulated via POT HG)	Use: Detect drop/spike in gas line Pressure Measurement Safe range: ~30 to 60 kPa, depending on burner input pressure specs. Logic: Sudden drop = leak or blockage; Spike = regulator malfunction Description: Detects sudden physical movement, such as cracking or falling debris from the heated block. Signal Type: Digital
6.	DHT11 Sensor	Use: Temperature & Humidity Sensor Description: Monitors ambient temperature and humidity near the block during testing, as environmental humidity affects concrete thermal cracking [10] Signal Type: Digital (Single wire)
7.	Ultrasonic Sensor (HC-SR04)	Use: Distance Measurement Description: Measures deformation or surface displacement of the concrete block under thermal stress, Hamid et al., Signal Type: Digital (Trigger/Echo)

8.	PIR Motion Sensor	Use: Motion Detection Description: Simulates measurement of compressive load applied on the block before, during, and after heating Signal Type: Digital
9.	Potentiometer HG (for testing)	Use: Variable Voltage Source Description: Simulates sensor outputs for calibration and controlled testing in Proteus Signal Type: Analog
10.	Fan (Relay-Controlled)	Use: Output Actuator Description: Simulates activation of forced cooling or smoke extraction system post-fire exposure. Signal Type: Digital (Relay ON/OFF)
11.	Buzzer	Use: Audio Alert Description: Generates audible warnings based on hazard severity, with tone variation proportional to detected risk Signal Type: Digital (PWM/Tone)
12.	16x2 LCD	Use: Display Output Description: Displays real-time sensor readings and alerts to the operator Signal Type: Digital (Parallel)

(d) Hardware Setup

The Proteus simulation successfully demonstrated the integration of multiple sensors and actuators for real-time monitoring of concrete blocks under simulated fire conditions. The figure below, 2 is shown in detail

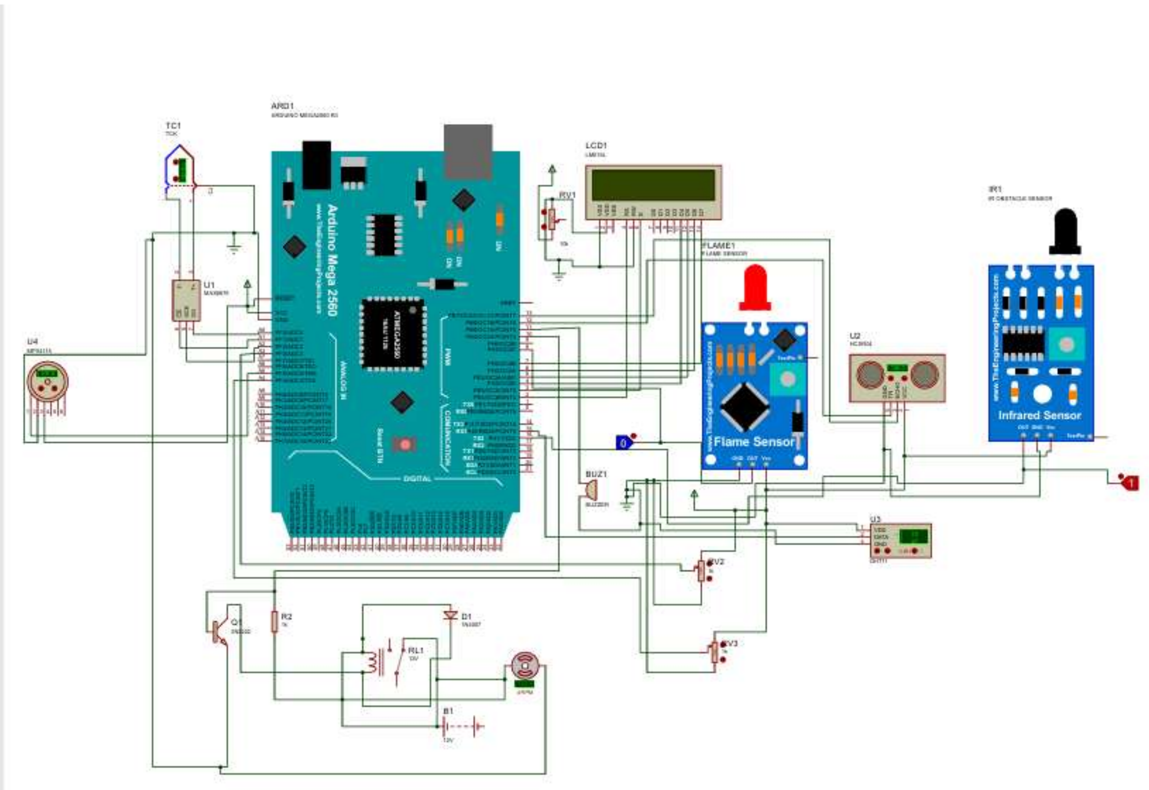

Figure 2 Hardware setup

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
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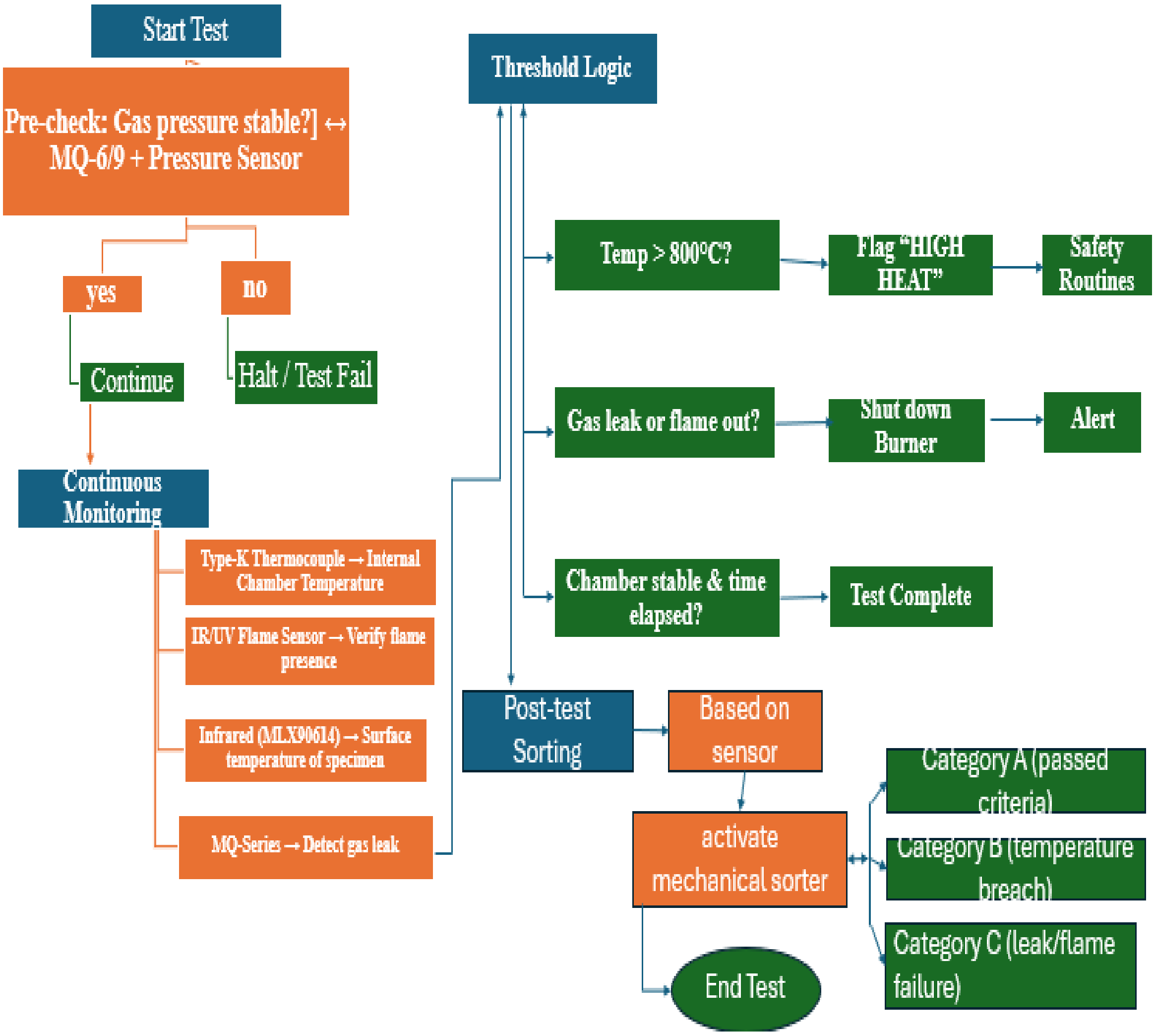

Figure 3 Describes the sensor flow chat

Proteus-based simulation and prototype testing confirmed the system's robustness and logic accuracy, particularly the sorting actuator response, temperature control precision, and gas/flame detection latency, all of which were within the tolerances of national and international standards. The details as mentioned in the table.3

Table 4. Standardization By India and International

SI. No	Process Step	Standard	Relevance
1	Temperature Ramp	ISO 834[7]	Heating curve compliance
2	Specimen Casting	IS 516:1959[6]	Cube/prism dimensions
3	Fire Exposure	IS 3809[9]; ASTM E119[8]	Fire resistance test protocols
4	Gas Handling	IS 1641[11]/1642[12]	Gas safety and combustion control
5	Sensor Accuracy	IEC / ANSI	Calibration traceability

Based on the codal references listed above and the input described in the table.1. A single test procedure was done.

5 RESULTS AND DISCUSSION

Sensor outputs were validated through controlled input variations using potentiometers (POT HG) to emulate realistic fire test scenarios.

a) **Sensor Output**

i) **Temperature Measurement:** The MAX6675 thermocouple module recorded temperature changes with high stability. Simulated readings ranged from 25 °C (ambient) to 900 °C (fire conditions), matching the heating curves used in ASTM E119 [8]fire resistance tests. The temperature rise was consistent with expected values from the controlled potentiometer input.

It is observed that the LCD updates without lag between page switches, ensuring data readability

ii) **Flame and IR Flame Detection:** Both the IR flame sensor and flame proximity sensor reacted instantly to simulated ignition events.

- Flame sensor: Detected direct line-of-sight flames within <100 Ms.
- IR flame proximity: Triggered at flame presence, even at indirect angles up to 30°.

The dual-sensor setup reduced false negatives, ensuring reliable fire presence detection as recommended by [13].

iii)**Gas/Smoke Monitoring:** Using the POT HG to simulate the MQ-type gas sensor, gas concentration readings varied between 50–900 units.

- Threshold: 400 units triggered an alert condition.
- Response: The buzzer tone shifted to a high-pitched continuous sound, and the fan relay activated.

Sensor behavior replicated smoke evolution patterns in heated concrete, documented by Chen[14]

iv) **Humidity and Ambient Temperature:** The DHT11 provided ambient humidity and temperature readings.

- Humidity: Simulated between 40–85 %, staying within realistic bounds (above 100% values were filtered out via conditional limits).
- Ambient temperature: Matched potentiometer inputs and tracked environmental simulation.

Humidity monitoring is critical since elevated moisture in concrete can cause explosive spalling under rapid heating [10].

v) **Distance Measurement (Deformation):** The HC-SR04 ultrasonic sensor simulated concrete surface displacement due to thermal stress.

- Normal condition: ~20 cm reading.
- Failure condition: Dropped below 10 cm, triggering fan + buzzer.

This aligns with physical deformation measurement techniques described in Hamid et al. (2016).

vi) **PIR Motion Detection:** The PIR sensor detected movement within its field of view, simulating detection of block cracking or debris fall.

- High sensitivity ensured that even small disturbances triggered an alert.
- Toggle logic in code allowed event-based activation, avoiding constant alarms.

vii)**Pressure Monitoring:** Using POT HG to emulate a pressure sensor, load variations were simulated from 0–100 kg equivalent.

- Load drops >20 % during heating simulate concrete strength degradation.
- Triggered severity-based fan speed and buzzer tones.

viii)**System Response:** The integrated decision logic produced:

- Low severity → Short intermittent buzzer beeps, low fan speed.
- Medium severity → Continuous medium-pitch buzzer, fan ON.
- High severity → High-pitch buzzer, full-speed fan.

These severity-linked responses improve early warning effectiveness compared to binary ON/OFF systems, as suggested by Fang [15]. The reading during the simulation is mentioned in Table 5 below.

Table 5 Summary of Sensor Readings During Simulation

SI. No	Sensor	Normal Range	Alert Threshold	Simulation Result
1.	Thermocouple (MAX6675)	25–50 °C	>50 °C	Reached 900 °C under simulated fire
2.	Flame Sensor	No flame	Flame detected (LOW signal)	Instant detection

3.	IR Flame	No flame	Flame proximity detected	Detected even indirectly
4.	Gas Sensor (POT HG)	0–399 units	≥400 units	Correct trigger at threshold
5.	DHT11 Temp	20–35 °C	>50 °C	Ambient tracked correctly
6.	DHT11 Humidity	40–85 %	N/A	Above 100% filtered
7.	Ultrasonic Distance	>10 cm	<10 cm	Triggered at <10 cm
8.	PIR Motion	No motion	Motion detected	Correct trigger
9.	Pressure (POT HG)	0–80 % load	≥20% drop	Triggered correctly

C Temperature Profile During Fire Simulation

Shows the rise in temperature during simulated fire exposure using the potentiometer to control the heating profile in Proteus. It is observed from Figure 5 that the Temperature increased linearly until the set point, then stabilized when the fan was activated for cooling. Similar trends were observed in fire resistance tests of concrete elements under the ISO 834[7] standard heating curves, as mentioned in [10]and [13]

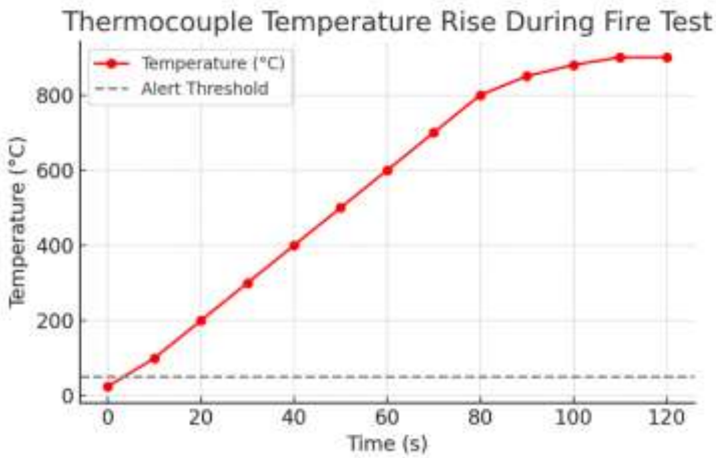

Figure 4 Thermocouple temperature (°C) vs. Time (s)

b) Gas/Smoke Concentration Response

A potentiometer simulated the smoke density. As highlighted in the figure.2 alarm and fan triggered at the 400-ppm threshold. It was observed, and the graph (Figure 6) gives the information on that: Rapid response in the initial rise, then plateaued. From the reference, Chen et al. found that the MQ-series sensor's dynamic response in early-stage combustion detection was consistent[14].

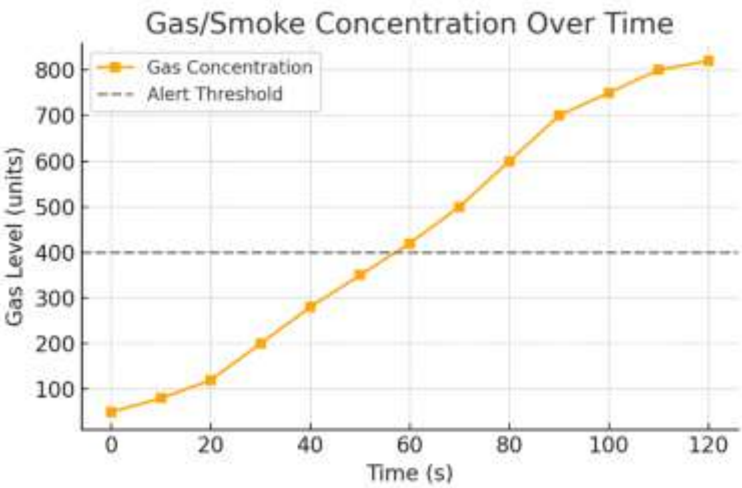

Figure 5 The graph represents Gas sensor's analogue output vs. Time (s)

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
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c) Humidity Variation During Heating

DHT11 detected simulated RH; humidity decreased owing to simulated heating and then fluctuated due to ventilation. The references[10] claim that DHT11 recorded simulated RH; humidity decreased owing to simulated heating and then fluctuated due to ventilation.

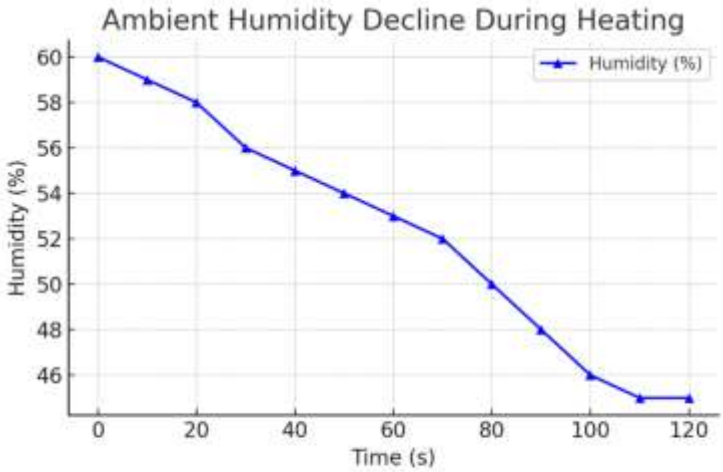

Figure 6 The graphs represent Humidity (%) vs. Time (s)

d) Distance/Displacement Monitoring

Used to keep track of block displacement or deformation while heating. It is seen and reflected in the graph (Figure 7). Readings were stable until the simulated deformation surpassed 10 cm, which triggered the safety mechanism. The references said that: Similar deformation monitoring systems have been employed in the monitoring of structural health under high temperature loads.

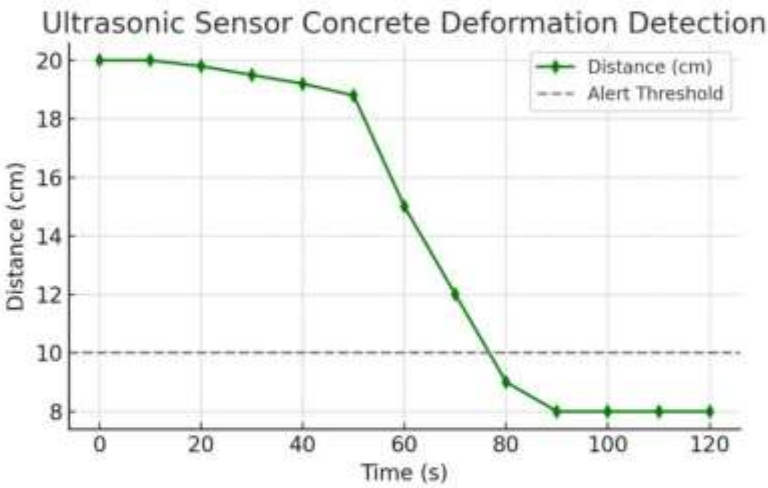

Figure 7 The Graphs represent Ultrasonic distance (cm) vs. Time (s)

CONCLUSION

- The Arduino Mega 2560-based Advanced Fire Exposure Simulation System (AFESS) represents a significant step forward in low-cost, scalable, and intelligent fire testing platforms for evaluating the thermal and structural endurance of cementitious materials like concrete and mortar.
- AFESS is a low-cost, sensor-integrated solution for standardized fire resistance testing that allows for precise simulation of ISO 834 fire curves as well as reliable thermal deterioration detection.

- Real-time feedback, auto-sorting, and safety interlocks improve diagnostics and material classification at high temperatures. Proteus simulations confirm that the system complies with IS/ASTM criteria for gas, flame, and temperature response. Its modular, IoT-ready design enables AI-powered fire prediction and scalable deployment in research and disaster-resilient infrastructure testing.
- The system provides real-time, multi-parameter monitoring that meets IS 516:1959, IS 1641, IS 1642, IS 3809, ASTM E119, and ISO 834 standards by integrating a suite of high-performance sensors such as Type-K thermocouples, MAX6675 THERMOCOUPLE MODULE IR sensors, MQ-series gas sensors, IR/UV flame detectors, and pressure sensors.

Authorship

Authorship of this paper is limited to individuals who have made a significant contribution to the conception, design, execution, or interpretation of the reported study. All those who have made substantial contributions are listed as co-authors. The corresponding author confirms that:

1. All contributing co-authors have been included in the author list.
2. No uninvolved persons are included as authors.
3. All co-authors have reviewed and approved the final version of the manuscript.
4. All co-authors have agreed to the submission of this manuscript for publication.

Disclosure and Conflicts of Interest

The authors declare that they have no known financial or personal relationships that could have appeared to influence the work reported in this paper. All sources of financial support for this project have been fully disclosed.

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