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# Design and Development of Drybath Incubator for Chemical Test Tubes with Fuzzy Logic Controller

**Dwi Hendra Yoga Priana[1], Vita Nurdinawati[2], Atika Hendryani[3]**
[1] Politeknik Kesehatan Kementerian Kesehatan Jakarta II, Jakarta, Indonesia
Corresponding author: Dwi Hendra Yoga Priana (e-mail: hendra.priana34@gmail.com)

**ABSTRACT** Clinical Pathology Laboratories require equipment for incubating samples and chemical reagents at temperatures between 25°C and 45°C. Commonly used water baths have limitations including contamination risk, temperature inaccuracy, and lack of incubation time display. Additionally, non-standard incubation practices such as holding test tubes in hands are often performed, reducing test result precision. This study aimed to design and build a dry bath incubator for chemical test tubes with a fuzzy logic-based temperature control system and integrated timer. The system employs a hollow aluminium block, cartridge heater, waterproof DS18B20 temperature sensor, Arduino Mega microcontroller, and a 3.5-inch TFT LCD touchscreen. The fuzzy logic controller regulates temperature from 25°C to 45°C. Testing included accuracy, stability, temperature distribution uniformity, and timer precision tests across 25 holes (20 holes Ø 1.25 cm and 5 holes Ø 1.5 cm). Results showed temperature accuracy of 99.99%–100.00%, temperature stability with fluctuations below ±0.4°C, uniform temperature distribution with 99.98%–100.00% accuracy, and timer accuracy of 99.994%. The system proved capable of replacing water baths as incubators for chemical reactions in clinical pathology laboratories.

**INDEX TERMS** chemical reaction tubes; dry bath incubator; fuzzy logic; laboratory incubator; temperature control

## I. INTRODUCTION

The rapid development of laboratory technology has driven the need for more precise ancillary equipment to support semi-automatic chemistry analyzers in Clinical Pathology Laboratories [1]. Water-based incubators (water baths) commonly used to date have inherent limitations: cross-contamination risk between the water medium and samples, temperature inaccuracy, and absence of an incubation time display [2][3].

Field observations further reveal that laboratory analysts frequently perform incubation using a non-standard method — holding test tubes by hand to utilize body heat. This practice substantially reduces the precision of test results [4]. Similar findings have been reported in previous studies on incubation-dependent clinical chemistry tests [5].

Dry bath incubators offer a cleaner and more precise alternative by using an aluminium block as the heating medium, thereby eliminating the contamination risk associated with liquid media. However, existing dry bath incubator research has been predominantly focused on microorganism incubation and neonatal incubators, leaving a gap in purpose-built designs for chemical reactions [6][7].

Putra et al. (2024) developed a dry bath incubator prototype using PWM control and a 20×4 dot-matrix LCD, lacking a touchscreen interface [2]. Ranchman (2020) designed a neonatal incubator with fuzzy logic using an LM35DZ sensor and a 2×16 LCD, with no heater safety mechanism [8]. Studies published in the Electromedic Journal further highlight the importance of precise temperature control in biomedical devices, particularly for incubation applications [14][15].

This study develops a drybath incubator specifically designed for chemical test tubes (3 ml and 5 ml) featuring a fuzzy logic controller, waterproof DS18B20 sensor, 3.5-inch TFT LCD touchscreen, thermofuse overheat protection, and voice-over alarm. The temperature range of 25°C–45°C was selected to meet the incubation requirements of End-Point chemical reaction methods [9].

## II. METHOD

### *A. SYSTEM DESIGN*

The system block diagram consists of an input block (3.5-inch TFT touchscreen), a processing block (Arduino Mega running the fuzzy logic algorithm), an output block (cartridge heater, cooling fan, speaker, display), and a sensor block (waterproof DS18B20). Key technical specifications are summarized in Table I.

TABLE I

TECHNICAL SPECIFICATIONS OF DRYBATH INCUBATOR

| Parameter | Specification |
|---|---|
| Temperature Range | 25°C – 45°C |
| Temperature Set Points | 25, 30, 37, 40, 45°C |
| Temperature Sensor | DS18B20 Waterproof |
| Heating Element | Cartridge Heater 8 mm |
| Mikrokontroler | Arduino Mega 2560 |
| Display | LCD TFT ILI9488 3,5 inci |
| Number of Holes | 25 holes (20 × Ø1.25 cm + 5 × Ø1.5 cm) |
| Timer | 1 – 60 minutes (1minute increments) |
| Safety Protection | Thermofuse + Solid State Relay |
| Power Supply | 220V AC / 50 Hz |

### *B. FUZZY LOGIC IMPLEMENTATION*

The fuzzy logic controller was implemented on the Arduino Mega using a Simplified Zero-Order Sugeno approach. The algorithm operates cyclically in real-time. System inputs are the temperature error (E = T_set − T_curr) and delta error (dE = rate of temperature change per second). Outputs are crisp constants (0, 15, 50, or 70%) converted to heater ON/OFF signals via Time Proportional Control [10].

#### 1) *System Initialization (void setup())*

```
void setup() {
  Serial.begin(9600);
  tft.begin(ID);
  sensors.begin();
  sensors.setWaitForConversion(false);
  sensors.requestTemperatures();
  pinMode(HEATER_PIN, OUTPUT);
  digitalWrite(HEATER_PIN, HIGH); // OFF
(High Trigger)
  windowStartTime = millis();
}
```

#### 2) *Temperature Data Acquisition (Sampling Rate 500 ms)*

```
const int TEMP_UPDATE_INTERVAL = 500;
void loop() {
  unsigned long now = millis();
  if (now - lastTempRequest >=
TEMP_UPDATE_INTERVAL) {
    float rawTemp =
sensors.getTempCByIndex(0);
    sensors.requestTemperatures();
    lastTempRequest = now;
  }
  // Compute Error & Delta Error
  smoothTemperature =
getSmoothedTemp(currentTemperature);
  inputError = (float)setTemperature -
smoothTemperature;
  float dt = (now - lastRateTime) / 1000.0;
  if (dt > 0)
    inputDError=(smoothTemperature-
lastTempForRate)/dt;
  lastTempForRate = smoothTemperature;
  lastRateTime = now;
}
```

#### 3) *Fuzzy Sugeno Function – Rule Base*

This function implements three main rules with a Strict Pulse mechanism to prevent overshoot caused by the thermal inertia of the aluminum block [11]:

```
float computeFuzzyLogic(float error, float
dError) {
  // SAFETY KILL SWITCH: If temp >= SetPoint,
shut off completely
  if (error <= 0.0) return 0.0;
   // Braking gap (2.0 for 25°C, 5.0 for
others)
  float brakingGap = (setTemperature <= 25) ?
2.0:5.0;
   // RULE 1: Far from set point -> High
Power (70%)
  if (error > brakingGap) {
    return (dError > 0.1) ? 50.0 : 70.0;
  }
```

```
  // RULE 2: Very Close (0-0.3°C) -> Strict
Pulse
  else if (error > 0.0 && error <= 0.3) {
    // Only apply 15% if temp is stable or
dropping
    if (dError <= 0.01) return 15.0;
    else return 0.0;  // Temp still rising ->
OFF
  }
  // RULE 3: Braking Zone -> Low Power
  else if (error > 0.3) {
    if (dError < 0.02) return 15.0;
    return 0.0;
  }
  return 0.0;
}
```

### *4) Time Proportional Control (Software PWM)*

The fuzzy output (0–100%) is converted to SSR ON/OFF signals within a 1000 ms time window:

```
// Window Size = 1000 ms (1 second)
if (now - windowStartTime >= SSR_WINDOW_SIZE)
  windowStartTime = now;
 // Convert Fuzzy Output (0-100) to On-Time
Duration (ms)
unsigned long onTime =
  (unsigned
long)((fuzzyOutput/100.0)*SSR_WINDOW_SIZE);
 // Execute SSR (Active Low Trigger)
if (fuzzyOutput > 0 &&
    (now - windowStartTime < onTime))
  digitalWrite(HEATER_PIN, LOW);  // Heater
ON
else
  digitalWrite(HEATER_PIN, HIGH); // Heater
OFF
```

### *5) Reset Logic and Timer Auto Unlock*

```
void presetTempSelected(int temp) {
  setTemperature = temp;
  tempReachedSoundPlayed = false;
  stableSoundPlayed = false;
  isStable = false;
}void handleTimer() {
  // ... (countdown logic) ...
  timerRunning = false;
  isAlarming = true;
  myDFPlayer.loop(3); // Play Alarm Track 003
  // Auto Unlock: allow settings to be
changed again
  isSettingsLocked = false;
}
```

## *C. TESTING METHOD*

Testing was performed using a calibrated standard thermometer placed at five sample hole positions (H1–H5: four corners and one center). Four types of tests were conducted:

1. Temperature accuracy test: 10 data readings at each set point (25, 30, 37, 40, 45°C)
2. Temperature stability test: recorded every minute for 15 minutes at steady-state condition
3. Temperature uniformity test: simultaneous measurement at 5 rows × 5 hole positions
4. Timer accuracy test: comparison of device timer against a calibrated standard stopwatch at durations of 1, 5, 10, and 15 minutes

Data analysis comprised mean values, absolute error, percentage error (%e), and percentage accuracy.

# III. RESULTS

## *A. TEMPERATURE ACCURACY TEST*

Temperature accuracy was evaluated with 10 repetitions at each set point. Table II summarizes the mean values and accuracy of the test results.

TABLE II
SUMMARY OF TEMPERATURE ACCURACY TEST RESULTS

| Set Point (°C) | Device Avg (°C) | Standard Avg (°C) | Error (°C) | Accuracy (%) |
|---|---|---|---|---|
| 25 | 25.2 | 25.4 | -0.3 | 99.99 |
| 30 | 30.2 | 30.4 | -0.2 | 99.99 |
| 37 | 37.2 | 37.1 | 0.1 | 100.00 |
| 40 | 40.2 | 39.9 | 0.2 | 99.99 |
| 45 | 45.1 | 44.8 | 0.3 | 99.99 |

Results demonstrate very high accuracy across all set points, with absolute error values ranging from 0.1°C to 0.3°C. Optimal performance was achieved at 37°C (100.00% accuracy), the critical incubation temperature for chemical reactions. The consistently small error values confirm excellent sensor response linearity across the entire tested temperature range.

## *B. TEMPERATURE STABILITY TEST*

Stability testing was conducted over 15 minutes at steady-state. At 25°C, all measurement points (H1–H5) maintained temperature within 25.4°C–26.0°C with highly linear, spike-free readings. At 30°C, measurement point H1 exhibited the highest accuracy (29.9°C–30.1°C) with an overall accuracy of 99.21%. At 45°C, accuracy reached 99.0% with a mean device reading of 45.1°C vs. 44.6°C standard. No significant temperature spikes were observed throughout all tests, confirming the effectiveness of the fuzzy logic algorithm in maintaining steady-state conditions.

### *C. TEMPERATURE DISTRIBUTION (UNIFORMITY) TEST*

Temperature uniformity testing evaluated heat distribution homogeneity across the entire incubator block. Table III presents the summarized results.

TABLE III

SUMMARY OF TEMPERATURE DISTRIBUTION (UNIFORMITY) TEST RESULTS

| Set Point (°C) | Avg Standard Temp (°C) | Error (°C) | Accuracy (%) |
|---|---|---|---|
| 25 | 25.7 | -0.4 | 99.98 |
| 30 | 30.5 | -0.3 | 99.99 |
| 37 | 37.2 | 0.04 | 99.999 |
| 40 | 40.1 | 0.04 | 99.999 |
| 45 | 44.9 | 0.2 | 100.00 |

Temperature distribution data shows that all five-hole rows (Rows 1–5) exhibit identical and uniform thermal characteristics. Scatter plot trendlines for each row converge into a single straight diagonal from 25°C to 45°C, confirming the absence of significant hot spots or cold spots. The aluminium block design and cartridge heater placement successfully achieved homogeneous heat distribution.

### *D. TIMER ACCURACY TEST*

TABLE IV

TIMER ACCURACY TEST RESULTS

| Duration (min) | Device Timer | Standard Timer | Error (sec) | Accuracy (%) |
|---|---|---|---|---|
| 1 | 01:00 | 01:00.1 | 0.1 | 99.983 |
| 5 | 05:00 | 05:00.1 | 0.1 | 99.997 |
| 10 | 10:00 | 10:00.1 | 0.1 | 99.998 |
| 15 | 15:00 | 15:00.2 | 0.2 | 99.998 |

Table IV presents the comparison of the device timer against a standard stopwatch across four duration settings.

The average timer accuracy reached 99.994% with a mean error of only 0.006%. The maximum time deviation recorded was 0.2 seconds at the 15-minute duration. These results confirm that the Arduino Mega microcontroller executes the countdown timer function with exceptional reliability for time-sensitive incubation processes.

## IV. DISCUSSION

The designed dry bath incubator system demonstrates superior temperature control performance compared to previous studies. The fuzzy logic algorithm with the strict pulse mechanism effectively prevents overshoot and maintains a steady state with minimal fluctuation, which is consistent with the findings reported by Tang and Ahmad (2024) on fuzzy logic control for nonlinear systems [12].

Compared to the PWM-controlled prototype by Putra et al. (2024), the fuzzy logic system in this study produces smoother temperature responses with real-time adaptive capability to ambient temperature changes [2]. The waterproof DS18B20 sensor, with a resolution of 0.0625°C, proved to deliver high reading accuracy across the entire tested temperature range, in agreement with prior studies on digital temperature sensors in biomedical applications [13].

The 3.5-inch TFT touchscreen interface offers a significant usability improvement over conventional push-button controls, fulfilling the user-friendly and intuitive design objectives. The voice-over alarm system via the DF Player Mini module provides audible notification when incubation time expires, enhancing operational safety in laboratory environments.

Limitations of this study include the absence of a data logger feature to record incubation history, and no direct testing with actual serum/plasma samples was performed. Future research is recommended to integrate IoT connectivity and a digital calibration menu within the touchscreen interface [14].

## V. CONCLUSION

This study successfully designed and implemented a dry bath incubator for chemical test tubes controlled by a fuzzy logic algorithm. The system achieved temperature accuracy of 99.99%–100.00% across all set points (25–45°C) with a maximum absolute error of 0.3°C. The strict pulse mechanism embedded in the Sugeno fuzzy controller effectively maintained steady-state temperature stability with fluctuations consistently below ±0.4°C, demonstrating the superiority of this approach over conventional PWM control. Temperature uniformity testing confirmed that heat distribution across all 25 holes of the aluminium incubator block was homogeneous, with accuracy ranging from 99.98% to 100.00%, verifying the suitability of the physical block design. The integrated digital timer achieved an average accuracy of 99.994% with a mean error of only 0.006%, confirming its reliability for time-sensitive incubation workflows. Overall, the device is proven suitable as a replacement for water baths in chemical reaction incubation within clinical pathology laboratories, offering a contamination-free, user-friendly, and precise alternative for End-Point chemical analysis methods.

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