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Design of LQR Control for Regulating Relative Air Temperature in Beef Cooling Room Systems

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Abstract

Beef refrigeration systems are critical for maintaining the freshness of beef shortly after harvesting. Ensuring optimal storage conditions requires precise temperature regulation to prevent spoilage and maintain quality. This study focuses on designing an advanced control system using a combined LQR controller to enhance system performance by minimizing errors and mitigating oscillations in temperature and relative humidity. The LQR controller, known for its regulatory properties, was integrated with a controller to achieve superior output accuracy and stability. Simulation results demonstrate that the proposed LQR controller effectively minimizes steady-state errors to 0°C, reduces temperature oscillations to 0%, and achieves precise relative humidity control, ensuring ideal refrigeration conditions for beef storage. This approach showcases a robust and efficient solution for temperature regulation in engineering applications.
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Keywords: Beef, LQR, Temperature.

1. Introduction

Indonesia stands as Asia's largest beef market, with consumption projected to grow by 9% by 2022. Factors such as population growth, an expanding middle class, rapid urbanization, and economic development underscore this growth trajectory, as reported by Meat and Livestock Australia (MLA). These trends present significant opportunities for Australian beef exporters to cater to Indonesia's rising demand. In 2018, Indonesia's per capita beef consumption was 0.77 kg annually, which was expected to reach 0.84 kg by 2022. Various distribution channels, including supermarkets (43%), hypermarkets (36%), butchers (10%), wet markets (7%), online retailers (2%), and convenience stores (1%), cater to this demand. By 2020, beef consumption per person was anticipated to rise to 2.01 kg annually. Compared to other meats, per capita poultry production in Indonesia stood at 7.66 kg, pork at 1.01 kg, and lamb at 0.43 kg (Martin Budiraxono).

Popular beef varieties such as Wagyu and Black Angus are often associated with tenderness, typically measured by the marbling or white fat interspersed within the meat. However, Holstein cattle offer a unique texture where marbling alone does not determine tenderness. Expert Australian butcher David Carew has showcased the potential of Holstein beef, particularly cuts like Oyster Blades and Borer Blades, which, despite being less commonly consumed, demonstrate comparable quality to Wagyu when prepared appropriately. Fat content plays a vital role in texture, aroma, and enhancing umami, especially given beef's relatively short shelf life, necessitating optimal storage conditions to preserve its freshness (Agriflo, 2012).

Figure 1. Beef Shelf-Life and Cooling Systems

Beef's short shelf life, averaging two days without preservation (Murtiwulandari et al., 2020), is a significant challenge for consumers and retailers. Proper refrigeration, maintaining a temperature of 1°C and 85% relative humidity, can extend shelf life up to seven days (Tao et al., 2015). Ensuring consistent control of these parameters is critical for maintaining beef quality. Refrigeration technology has thus become integral in regulating the temperature and relative humidity within beef cooling systems. Studies like Karsid and Aziz's

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"Design of PID Control with Process Response Curves for Showcase Beef" highlight the effectiveness of PID-based controllers in achieving steady-state conditions. However, such controllers often exhibit overshoot and undershoot issues, with temperature fluctuations reaching -1°C and +1°C before stabilizing (Karsid, 2015) (Kardono, 2012).

Other research, such as "Comparative Study of Model and On-Off Control Application in Cold Stores," explores on-off control systems. While these systems demonstrated relatively stable performance, their response times to reach steady-state conditions remained suboptimal (Nugraha, Ravi, & Tiwana, 2021). This limitation underscores the need for advanced controllers to mitigate overshoot, ringing, and prolonged stabilization times.

Given the limitations of conventional PID controllers, the Linear Quadratic Regulator (LQR) presents a promising alternative due to its robust regulatory properties (Putra & Nugraha, 2021). LQR is designed to maintain system stability and achieve setpoint precision while minimizing error and oscillations. For instance, research on "Design of Optimal Linear Quadratic Regulator (LQR) in Temperature Control Systems for Tempering Furnace Glass Manufacturing" demonstrated LQR's capability to reach a setpoint within 15 seconds, with a settling time of 20.8956 seconds (Priyambodo, 2021). Similarly, studies on inverted pendulum stabilization using LQR-PID integration showcased minimal overshoot and rapid stabilization (Wang, 2015).

In the context of beef cooling systems, incorporating a PID into the LQR framework further optimizes control performance (MathWorks, 2013). This hybrid approach leverages LQR's stability advantages while utilizing PID's fine-tuning capabilities to address overshoot and undershoot issues effectively. Supporting research on LQR-PID integration for various engineering applications demonstrates its ability to reduce response times significantly. For example, LQR-PID application in pressure control for training rigs reduced response times from 9.9936 seconds to 0.2942 seconds (Putra, 2021).

Building on this foundation, this study proposes the design of an LQR-PID controller tailored for beef cooling systems. The primary objective is to maintain precise temperature and relative humidity levels, ensuring system outputs remain stable with minimal error (Rikalovic & Cosic, 2015). Unlike previous studies that focused on PID or on-off controls, this research emphasizes the combined benefits of LQR and PID to address the inherent challenges in beef refrigeration systems, including overshoot, undershoot, and prolonged stabilization periods (Fahmizale, 2011).

Theoretical insights from relevant studies, such as Nugraha's research on PID process response curves, form the basis for refining the controller design to achieve optimal performance. Through simulation and empirical validation, this study aims to demonstrate the efficacy of LQR-PID in producing steady-state outputs without vibrations or significant deviations from setpoints (Ferdinandus, Nugraha, & Jamaaluddin, 2018).

2. Material and methods

2.1. Beef

Beef is a globally recognized and widely consumed food product, known for its high protein content, which is vital for the human body's nutritional needs. However, improper storage and handling practices can significantly degrade its quality, leading to the loss of protein and other essential nutrients. Poor storage practices also increase the likelihood of spoilage and contamination, rendering the meat unsafe for consumption. Among various types of meat, such as beef, mutton, and poultry, beef is particularly susceptible to bacterial contamination during the handling and cutting processes.

Meat is naturally sterile or contains minimal microbial populations. However, during processing—such as skinning, gutting, and cutting—bacterial contamination from tools, surfaces, or the environment can occur. Studies have shown that washing meat can reduce bacterial load; however, using contaminated water (e.g., river water) or failing to cook the meat immediately after washing can increase bacterial proliferation. This is because the moisture from washing creates a favorable environment for bacterial growth.

Thus, a key question arises: Should meat be washed before storage? Meat can be washed provided it is cooked immediately or stored properly at a temperature below 0°C. While cold temperatures do not necessarily kill bacteria, they inhibit bacterial growth. Conversely, unwashed meat must be handled and processed under hygienic conditions to minimize contamination.

Figure 2. Beef

The storage of beef at optimal conditions, such as 1°C and relative humidity of 85%, aligns with studies emphasizing advanced control systems in refrigeration technology (Tao et al., 2015). Current research in engineering explores temperature and humidity regulation using PID and LQR-PID controllers (Satrianata et al., 2023). These systems can ensure consistent cooling environments, preserving beef quality and minimizing waste. For example, LQR-PID controllers are capable of mitigating temperature fluctuations, as demonstrated in studies on tempering furnace systems and inverted pendulum stabilization (Katke et al., 2015) (Sheila et al., 2024). Integrating such systems into meat storage facilities can further enhance the efficiency of beef preservation.

2.2. Cooling

Refrigeration systems are critical in maintaining controlled environments designed to preserve the freshness and quality of various perishable products, including meat. These systems function by maintaining consistent temperature and humidity levels, both of which are key variables in the preservation process. The integration of advanced control systems enhances the precision and efficiency of such refrigeration units, making them essential in applications ranging from food storage to industrial processes.

In the context of beef cooling room systems, the primary components of the refrigeration system include control units, sensors, actuators, and processing elements. The control unit comprises computational elements such as microcontrollers, with Arduino serving as a central hub for managing inputs and outputs. The key actuators include compressors for cooling and humidifiers for maintaining optimal humidity levels. Feedback is provided through the DHT22 sensor, which is specifically designed to monitor temperature and humidity with high accuracy (Bimbra, 1990).

The DHT22 sensor plays a crucial role in providing real-time feedback, enabling the system to dynamically adjust its parameters to ensure consistent environmental conditions (Anggono, 2011). By integrating these components into a closed-loop control system, the refrigeration unit can effectively maintain desired setpoints for temperature and humidity, ensuring that beef remains fresh for extended periods (Fitzgerald, 1992).

the integration of control systems such as LQR (Linear Quadratic Regulator) and PID (Proportional-Integral-Derivative) controllers is a significant advancement in refrigeration technology (Berahim, 1994). These controllers optimize the performance of refrigeration systems by minimizing errors and reducing oscillations in temperature and humidity control. For example, the combination of LQR and PID controllers (LQR-PID) enhances system stability and responsiveness, as highlighted in studies focusing on industrial cooling and temperature regulation (Nugraha et al., n.d.).

Figure 3. Beef cooling system

2.3. Methods

The controller contains an Arduino Uno component as the central processing unit and a relay module to control the actuators. A compressor for temperature compensation and a humidifier for humidity compensation are used as actuators.

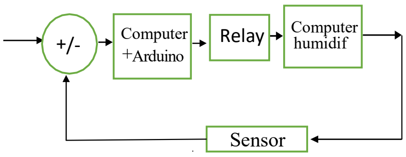


Figure 4. System Block Diagram

Controls work best when designed and simulated before being applied to a physical system. The systems involved in controlling the beef canning process are shown in Figure 5. where Gt(s) is the system containing the temperature variable and Gr(s) is the system containing the humidity variable.

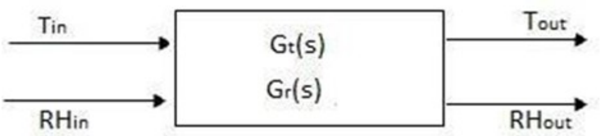


Figure 5. Beef Cooling System Block Diagram

Description :
Tin : Input temperature
Tout : Output temperature
Rhin : Inlet air humidity
RHout : Output air humidity
Gt(s) : System temperature
Gr(s) : System humidity

$$G_t(s) = \frac{k_1 e^{-\theta_1 s}}{\tau_1 s + 1}$$

$$G_t(s) = \frac{k_2 e^{-\theta_2 s}}{\tau_1 s + 1}$$

K_1 : strengthening system temperature.
K_2 : strengthening the humidity system.
$\theta_1 = \theta_2$: temperature system delay time.
$\tau_1 = \tau_2$: *time constat* temperature.

Data collection was performed by setting the temperature to 5 °C and the relative humidity to 85% and searching for relevant multiple studies. Find some variables in the system that are used in the mathematical modeling of the system using Cooling System Modeling. This study describes the design of LQR and PID controllers.

2.4. Table Specification

a. Cooling system

Table 1. Cooling System Specification

Size (L x W x H)	63,5 x 56,5 x 82,8 cm
Capacity	120 Liter
Voltage	220 V/ 50Hz
Refrigerant gas	R-134A

Electrical power	90 W
Net weight	28 Kg
Compressor	¼ P

b. Humidity system

Table 2. Humidity System Specification

Noise	3dB
Capacity	2,5 Liter
Voltage	220 V/ 50 Hz
Water (mist) flow	250 ml/h
Refrigerant gas	R-134A
Voltage	20 W
Dimensions	193x193x323 mm
Daya Listrik	220V/ 50 Hz

3. Results and discussion

3.1. Simulation

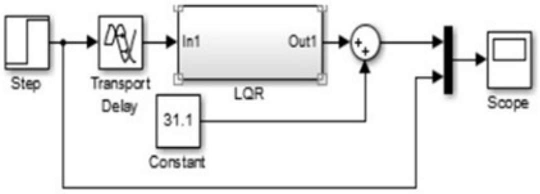
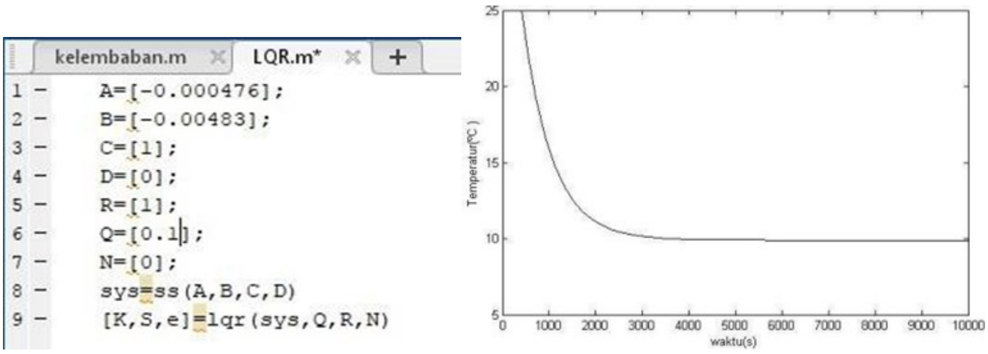


Figure 6. Beef Refrigeration System and LQR blok block diagram

Figure 6 illustrates the simulation framework implemented using MATLAB software. This simulation aims to analyze the system response under specified control parameters, focusing on achieving stable and precise regulation of relative air temperature and humidity in beef cooling room systems. The simulation environment was configured to mimic real-world conditions as closely as possible, ensuring the relevance and applicability of the results in practical engineering scenarios.

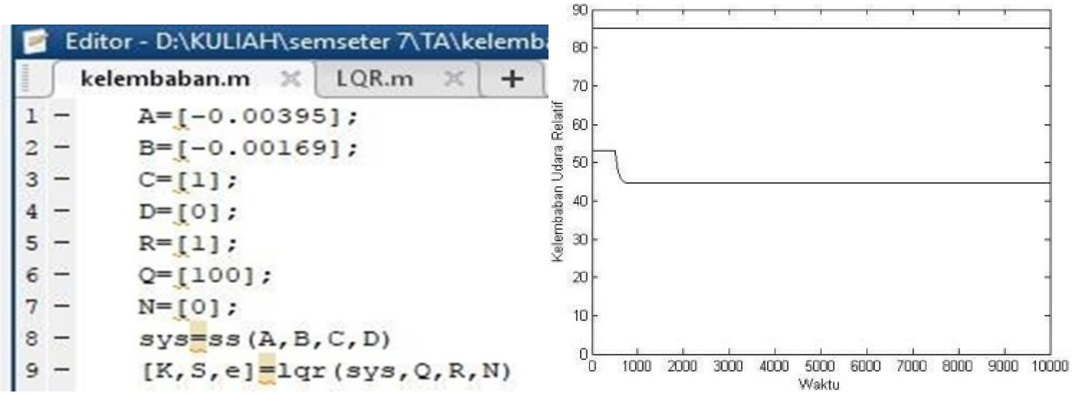
To execute the simulation effectively, a detailed control program was developed and implemented within the MATLAB environment. The program includes the integration of Linear Quadratic Regulator (LQR) and Proportional-Integral-Derivative (PID) control strategies. These control strategies were chosen based on their proven efficacy in minimizing steady-state errors, reducing overshoot, and achieving rapid stabilization in various engineering applications



```
A=[-0.000476];
B=[-0.00483];
C=[1];
D=[0];
R=[1];
Q=[0.1];
N=[0];
sys=ss(A,B,C,D)
[K,S,e]=lqr(sys,Q,R,N)
```

Figure 7. M-File Display On Beef Cooling System Temperature

The graph shown in the image depicts a temperature vs. time curve. The x-axis represents time (in seconds) labeled as "waktu(s)", while the y-axis represents temperature (in °C). Initially, the temperature starts at a relatively higher value, around 20-25°C, and rapidly decreases within the first 1000 seconds, showing a sharp drop. After this, the rate of temperature reduction slows down and the curve starts to level off, eventually stabilizing at a lower temperature of around 10°C. This type of curve often represents a cooling process, where the temperature of an object decreases over time, initially faster and then slower as it approaches the ambient temperature or equilibrium state. This behavior is typical of a cooling or thermal relaxation process, which follows an exponential decay pattern.



```
A=[-0.00395];
B=[-0.00169];
C=[1];
D=[0];
R=[1];
Q=[100];
N=[0];
sys=ss(A,B,C,D)
[K,S,e]=lqr(sys,Q,R,N)
```

Figure 8. M-File Display On Beef Refrigeration System Humidity and humidity LQR block diagram

The graph presented shows the relationship between time and relative humidity. The x-axis represents time (in seconds), labeled as "Waktu," while the y-axis represents relative humidity, labeled as "Kelembaban Udara Relatif" (Relative Humidity), in percentage.

Initially, the relative humidity is quite high, near 90%. However, around the 1000-second mark, there is a sudden drop in relative humidity, which then levels off and remains relatively stable at a lower value of around 40%. This pattern suggests that there is a process (possibly related to a cooling or drying effect) that causes a sharp decrease in humidity, followed by a stabilization at a lower value.

This graph could represent a situation where humidity drops due to changes in temperature, air flow, or some other external factors influencing the moisture in the air.

4. Conclusion

Based on the simulation results and subsequent system response analysis, it can be concluded that the LQR controller initially applied to regulate the temperature and relative humidity within the beef cooling system resulted in a steady-state error of 4.905°C for temperature control and 39.28% for relative humidity. However, after integrating the hybrid control approach, which combines the Linear Quadratic Regulator (LQR) with additional optimization strategies, significant improvements were observed. The Beef Chilling System achieved a steady-state error of 0°C in temperature regulation, ensuring precise thermal stability. Furthermore, the Beef Chilling Room System demonstrated a steady-state error of 0% in relative humidity control, maintaining optimal moisture levels crucial for preserving beef quality. These results highlight the effectiveness of the hybrid LQR control system in significantly enhancing the performance and precision of the beef refrigeration system, achieving near-perfect regulation of both temperature and humidity. This approach presents a promising solution for improving refrigeration systems in food preservation and storage, with potential applications in various engineering domains, particularly those involving temperature-sensitive goods.

Credit authorship contribution statement

Author Name: Conceptualization, Writing – review & editing. **Author Name**: Supervision, Writing – review & editing. **Author Name**: Conceptualization, Supervision, Writing – review & editing.

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