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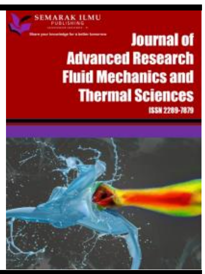

Advancing Passenger Comfort: Creating a Prototype for Thermal Comfort Clothing in Flight Cabins

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ABSTRACT

Research on thermal comfort has demonstrated that individuals possess unique comfort preferences in specific thermal environments. The concept of thermal comfort clothing for individuals was rarely found in previous studies. The objective of this research is to create a prototype that can sustain a thermally comfortable in winter condition for passengers in the airplane cabin. The thermal clothing was designed and put to the test in real-world scenarios to evaluate its efficacy. The outcomes of the tests were verified by assessing the levels of thermal comfort. The functionality of the clothing system revolved around heating water with a heater and then circulating it through tubes embedded within the clothing. The heat from the water was transmitted to the wearer, resulting in an increase in temperature from 22 degrees Celsius to 25 degrees Celsius within a span of 15 minutes. From the result obtained, the trend lines for surrounding temperature and water temperature exhibit a direct correlation. When the surrounding air temperature decreases, the water temperature also decreases over time. Both trend lines demonstrate a consistent increase in temperature at the same rate. Additionally, the break-even point for both trend lines occurs at 25°C in zero seconds, indicating that the prototype begins to influence the surrounding temperature in relation to the water temperature.

1. Introduction

Numerous studies have focused on thermal comfort and energy efficiency [1-10]. In recent years, thermal comfort research has gained significant attention worldwide, potentially due to the growing discourse on climate change. Evaluating overall thermal comfort and indoor environmental quality goes beyond purely considering physical parameters. The human body's physiological and psychological responses to the environment are dynamic and encompass various physical factors that interact within space, including light, noise, vibration, temperature, humidity, and more [11]. The

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complexity of evaluating these environments is exemplified by the specialization of existing standards that aim to analyze and enhance individual aspects such as thermal, lighting, and acoustics. In the realm of thermal comfort, widely adopted international standards for assessing thermal environments include ISO 7730-2005, ASHRAE 55-2013, and EN 15251-2007 [11-13].

According to Lee *et al.,* [14], Creating a comfortable atmosphere within aircraft cabins is a primary consideration in mass transit. The aspects that passengers most commonly express dissatisfaction with include humidity, temperature, odors, and noise. Attaining a specific level of thermal comfort becomes particularly challenging, especially when traveling in an airplane at high altitudes. Limited options are available inside an aircraft to address comfort concerns, such as installing larger fans during hot weather or activating heaters on cold winter days. As highlighted by Sun *et al.,* [15], passenger expectations for comfort are continually increasing on domestic and international flights. Consequently, it is necessary to take further measures to achieve an appropriate level of thermal comfort for passengers.

Controlling temperature is a significant factor in regulating thermal comfort. To attain a comfortable level, the temperature needs to be adjusted accordingly, either increasing or decreasing depending on the surrounding environment [16]. However, it can be challenging to control the ambient temperature effectively. As a solution, devices have been developed to manage and provide optimal temperatures for achieving thermal comfort. Various types of temperature control and portable devices are currently available for use in flights. Despite their availability, the utilization of such devices remains limited.

In their comprehensive overview, Streblow *et al.,* [17] categorized the existing thermal comfort models into two main groups: models utilizing a statistical approach and models utilizing a physiological approach. Statistical models predominantly outline mathematical correlations between the environment and subjective perceptions (for instance, the Predicted Mean Vote, PMV), whereas physiological models offer detailed analyses of physical processes such as heat transfer, particularly in unique climatic conditions [18-20].

Until this point, only a limited amount of research has addressed the cumulative impact of multiple climate parameters on thermal comfort and the interconnections among them within aircraft cabins. Grun *et al.,* [21] examined the simultaneous influence of temperature, humidity, noise, and pressure on thermal comfort within an aircraft cabin. The associations between temperature, noise, and thermal comfort were substantiated, while humidity was found to have no effect in the predictive equation. Collectively, their findings indicate the necessity for a more comprehensive approach to future investigations concerning thermal comfort.

Previous research has explored the spectrum of variations in thermal comfort, revealing that individuals exhibit specific preferences for comfort within distinct temperature ranges [22-25]. Building upon this notion, the current study is dedicated to the design, development, and testing of thermal clothing. The primary goal is to address the challenge of winter weather to ensuring optimal thermal comfort using clothing and aiming to provide an enhanced level of comfort for middle range flight.

2. Methodology

2.1 System Design Selection

Limited research has been conducted on the integration of thermal comfort in human clothing. However, researchers have come across numerous papers focusing on well-established design systems, particularly those pertaining to thermal comfort in buildings and cabins. Recent studies have indirectly addressed low-temperature heating applications by conducting comprehensive reviews of building life cycles or investigating specific aspects. As a result, the subsequent investigation of low-temperature hydronic space heating systems is both novel and relevant in the present context [26].

Modern hydronic technology is a medium that skilled designers can use to create an appropriate heating or cooling solution for almost any building. The universal system of modern hydronic technology is compatible for both heating and cooling buildings. This section highlights the benefits of modern hydronic systems, both to those designing and installing systems, and to the occupants of buildings that are heated by hydronic technology. It is essential that heating experts understand the basics of these benefits and effectively inform those who are trying to select a means of heating suitable for their building [27,28].

The process begins with Hydronic Heating, where water is heated efficiently at its source using highly energy-efficient gas boilers. After being used, the water is circulated back for reheating through a recirculating system. This dedicated 'heating' system is distinct from the household's domestic hot water supply. In each room, panel radiators serve as 'Heat Emitters,' emitting natural radiant heat that spreads uniformly. These radiators are adjustable on an individual basis, allowing for optimal comfort in each room, with the flexibility to create warmer living areas compared to bedrooms. Importantly, this system stands apart from air-forced central heating systems by eliminating airborne particles, as illustrate in Figure 1.

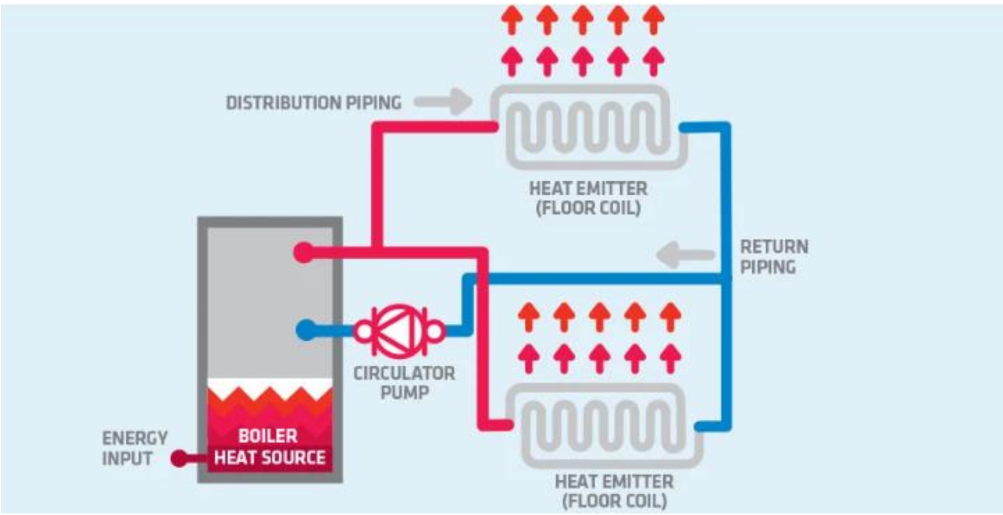

Fig. 1. Layout of modern hydronic heating system for heating

2.2 Proposed Design System

The proposed system designs have been derived from the hydronic heating system to guarantee the operational efficiency of the prototype. Figure 2 provides a visual representation of the proposed design device, presenting a schematic drawing that demonstrates the necessary connections for each component to function effectively. The power supply output is linked to a switch, which subsequently connects to both the pump and the heater.

Even in moments of dormancy, the power supply surrenders to the paradox of existence, ceaselessly bestowing its electric embrace upon the waiting components, succumbing to the inevitability of energy losses. Through a network of interconnectedness, the very essence of vitality flows from the power supply to the pump, the temperature controller, and the heater, instilling life into the heart of the system. Each connection is meticulously crafted, a testament to the quest for efficiency, ensuring that the symphony of functionality orchestrates flawlessly. Behold the temperature controller, adorned with four connectors, each bearing the vibrant mark of a specific hue, like a spectral guide to their intended destinations. Let this knowledge be etched in the annals of experimental work, a beacon of insight illuminating the path ahead.

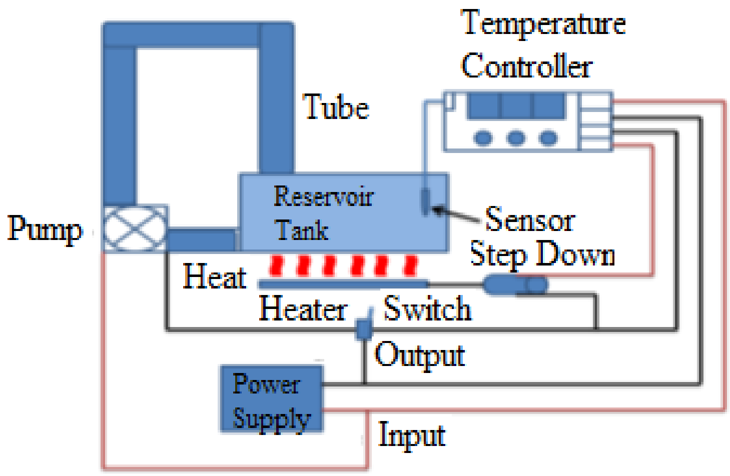

Fig. 2. Schematic Drawing of the Proposed Design

2.3 Prototype Development

Comprehensive details regarding product development have been shared with researchers to improve their comprehension and enable effective knowledge dissemination among their peers. Table 1 tabulates the bill of materials (BOM) employed in this project, while Table 2 presents both the item count and unit prices. The total expenditure for creating this prototype falls within the confines of the provided grant. The proposed design serves as a guide for the selection of suitable components in prototype construction. It is imperative to grasp the prerequisites associated with the components employed in this project.

Table 1
Bill of Material (BOM)

Bil	Description	Unit
1	Water pump	1 piece
2	Temperature controller	1 piece
3	Warmer plate	1 piece
4	AC/DC Adaptor	1 piece
5	6 Pin switch	1 piece
6	USB cable wire	1 packet
7	Tube	7 meter
8	12 volt battery (power supply)	1 piece
9	Crocodile clip wire	1 packet
10	Safety vest	1 piece
11	Container	1 packet

Table 2
Detail List of Components

No	Description	Material/Equipment	Specification
1	DC 12V Brushless Water Pump Waterproof Submersible		• Input voltage: 3.5V to 12V DC (50mA-500mA) • Max volume: 350L/h • Size: 3.75 × 3.71 × 3.3cm • High temperature version: Max 80°C • 3.5mm cable and waterproof connector
2	12V Digital Temperature Controller with Sensor		• Temperature control range: -50 – 110°C • Measure accuracy: 0.1°C • Input power: DC 12V • Output: one way 10A relay • Size: 48 × 40mm
3	5V USB Cup Warmer		• Electric current: 750mA • 13.6 × 10.6 × 1 cm • Power: 3.75W • Voltage: 5V DC
4	12V/1.0A Switching Adaptor		• Input: 100-240V AC 50/60Hz • Output: 12V DC 1000mA • Plug type: 3 pin plug (Malaysia Standard) • DC jack: center positive with connector size 2.1 × 5.5mm jack
5	6 Pin (ON-ON/DPDT) Toggle Switch		
6	USB Cable wire		

7	Tube		• Length: 7 m
8	Power supply / battery		• Voltage: 12 volt
9	Safety vest		

2.3.1 Assembly procedure

In this section, the step-by-step assembly or setup of the prototype will be explained, component by component. This detailed explanation aims to provide clarity and guide the order of component assembly. The selected materials are then placed within a specifically designed casing. The sequence of assembly is as follows:

(i) Pump: The pump's purpose is to circulate water from the reservoir tank throughout the tube system. By utilizing the pump, the water flow velocity within the tube increases. One end of the pump is connected to the reservoir tank through a tube, while the other end is connected to the opposite end of the tank.
(ii) Temperature controller: Equipped with a digital display, the temperature controller provides the current temperature reading of the water inside the reservoir tank using a sensor. Once the water reaches the desired level of warmth, the temperature controller automatically switches off the connected heating element.
(iii) Heating element: The heating element is responsible for warming the water within the reservoir tank. It is essential to ensure that the heating element operates at a voltage below 5 volts to prevent boiling the water. The heating element is connected to the temperature controller, allowing it to switch off once the desired temperature is reached.
(iv) Smoke socket and USB port: The smoke socket is connected to the USB port adaptor to account for the voltage difference. The smoke socket operates at 12 volts, while the USB port adaptor provides 5 volts. Therefore, a step-up mechanism is required to increase the voltage from 5 volts to 12 volts for the smoke socket to connect to the 12-volt adaptor.
(v) Toggle switch: The toggle switch is connected to both the pump and heating element. Its purpose is to prepare the pump and heating element in standby mode. Once the device is connected to a power supply, the toggle switch is turned on to activate the pump and heating element.

(vi) Adaptor: The adaptor facilitates the connection between the power supply and the device. Once the adaptor is connected to the power supply, it automatically powers on the device. However, the pump and heating element remain in standby mode until further activation. The adaptor used operates at 12 volts with 1.0 ampere to support the entire device's functionality.

The system's prototype, depicted in Figure 3, has been developed independently from the clothing. Notably, this system will be attached to the attire situated beneath a safety vest. This arrangement is meticulously orchestrated to emulate the clothing setup of airplane passengers, thus ensuring a precise and faithful representation. In accordance with best practices in research and experimental design, it is essential to maintain a high degree of realism in prototypes to draw reliable conclusions. This approach helps to simulate real-world conditions as closely as possible, enabling the most accurate evaluation of the system's performance.

Fig. 3. Heating system prototype and heating system install to the cloth

2.4 Experimental Setup

The data collected and recorded is taken using standard equipment such as the manual thermometer. A mercury thermometer which is obtained from any store or pharmacist such as the

Caring, Watson and many more is used to take the temperature reading of the surrounding temperature. As for the water temperature, the reading is said to be accurate because a temperature controller with sensor is used to record the reading of the water temperature.

The time taken for the water temperature to achieve the required temperature is taken by using a stopwatch available in any phones. It is important to get the time taken for this project because since the prototype, it is a must to make sure that the product does not consume that much time and to achieve the sufficient heat energy for power efficiency of the prototype and see how far the new design can achieve.

(i) Connect the device to a power supply and switch it on. Check if the digital display on the temperature controller is functioning by ensuring that it shows a display. Set the desired temperature for the device to activate its cut-off feature.
(ii) Switch on the toggle switch to activate both the pump and heating element. Verify that the pump is running, and the heating element is operational.
(iii) Allow the device to run for a few minutes, and then measure the temperature of the water using a thermometer. Use a stopwatch to record the time taken for the water to reach the desired warmth.
(iv) Monitor the hose for any potential leakage while the device is in operation.
(v) After turning off the heater, stop the timer and record the time required for the device to terminate its operations. Perform multiple tests to determine the average time required.

Once the individual components have been evaluated, integrate them to create a prototype device capable of adjusting the thermal comfort of an individual in an aircraft passenger cabin.

3. Results and Discussion

Table 3 presents three key parameters: surrounding temperature, water temperature, and the time it takes for the water to adjust to the surrounding temperature as it decreases. The surrounding temperature is measured using a standard thermometer, while the water temperature is accurately recorded using a temperature controller with a sensor. Unlike the surrounding temperature, which can be influenced by climate or weather changes, the water temperature remains unaffected. The time taken for the water temperature to change is longest when the surrounding temperature decreases, with no changes occurring within the thermal comfort range. Additionally, the prototype's condition is monitored to verify its proper functionality and adherence to programming.

Table 3
Data of the 3 parameters get from the experiments

Surrounding temperature (°C)	Water temperature (°C)	Time taken (s)	Condition (ON/OFF)
22.3	23.2	660	ON
21.7	22.6	840	ON
21.2	22.1	900	ON
20.8	21.7	1920	ON
31	30.2	0	OFF
28	29.5	0	OFF
27	27.7	0	OFF
24	25.3	0	OFF

From the result obtain, three parameters were measured, which are the surrounding temperature, water temperature and time taken for the temperature to change. For each parameter, the graphical significance of the relationships among the selected variables was determined. There are extended results and in-depth discussions on this topic. To help the readers better understand the results, graphs and figures were provided. The three main parameters for this prototype are surrounding temperature, water temperature, and time taken, as shown in Table 3. Additionally, the condition of the prototype during the experiment was also taken into consideration.

Figure 4 depicts the fluctuation of temperatures over time for both the surrounding air and water, highlighting their progression towards the desired temperature. Notably, distinct patterns emerge between the trend lines of the surrounding air and water temperatures within a specific timeframe. During the temperature range of 30°C to 24°C, the surrounding temperature remains constant at zero seconds. This extended period of stability arises from the slow and gradual changes in the surrounding temperature, which sometimes necessitate several days to obtain a consistent measurement. Accurate monitoring of the surrounding temperature is crucial to assess the efficiency of the prototype. Furthermore, the temperature of the surrounding air experiences fluctuations in response to climate variations, where rainfall contributes to lower night-time readings and daytime sunlight leads to higher temperature measurements.

The surrounding temperature remains nearly constant between 600 seconds and 2000 seconds (approximately 10 to 30 minutes) when it is below 24°C, indicating that the prototype's impact on the temperature is minimal within this range. The prototype demonstrates higher efficiency from 22°C onwards, but as the surrounding temperature decreases, the time required to reach the desired temperature increases, suggesting reduced efficiency. In contrast, the water temperature is influenced by the surrounding temperature, and the reading is crucial to evaluate the prototype's effectiveness. The water temperature changes according to the climate variations in the surroundings, with higher surrounding temperatures leading to faster changes in the water temperature. However, the prototype only operates efficiently in lower temperatures. From 600 seconds to 2000 seconds, the trend line shows a relatively constant water temperature below 24°C. The prototype's impact becomes noticeable from temperatures of 22°C onwards. However, as the surrounding temperature decreases further, the final readings take longer, indicating reduced prototype efficiency.

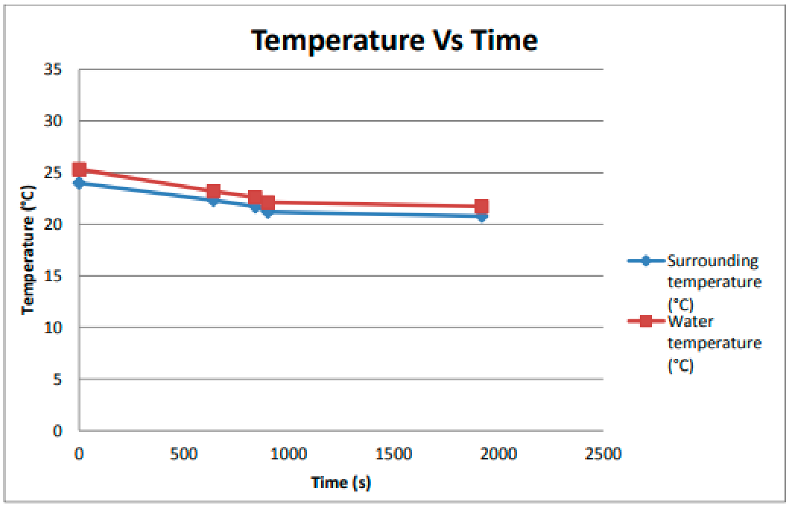

Fig. 4. Result for temperature vs time for surrounding temperature and water temperature

3.1 Data Validation

A 5-volt USB heater was utilized for this prototype. The key data of the heater plate used in the calculation served specific functions and held values required to calculate heat transfer and other relevant information. The subsequent step involved expanding the heat convection equation to accommodate the prototype's utilization of the convection method, which considered the fluid's motion through the container and tube. This extended equation facilitated the determination of the temperature distribution in both the surrounding environment and the water, allowing for the calculation of heat transfer, denoted as Q, using Fourier's Law of convection, which will be further elucidated.

3.1.1 Experimental calculation

<u>Heat transfer from heater</u>

Given:

Convection, h = 10 W/m². °C (minimum of free convection)

Area, $A = \pi r^2$ (1)
$= \pi (0.065)^2$
$= 0.015\ m^2$

Temperature of heater, Ts = 80 °C (maximum)

Temperature of water, T∞ = 21.7 °C (water)

Heat transfer, Qconv = H x A (Ts - T∞)
= 10 W/m². °C x 0.013 m² x (80 °C – 21.7 °C)
= 7.67 W

3.1.2 Theoretical calculation

<u>Heat transfer in plastic container</u>

Given:

Convection, h = 10 W/m². °C (minimum of free convection)

Area, $A = (\pi rh+\pi r^2) + (\pi rh+\pi r^2)$ (2)
$= (\pi (0.045)(0.065) + \pi (0.045)^2) + (\pi (0.06)(0.065) + \pi (0.06)^2)$
$= 0.04\ m^2$

Temperature of surrounding, Ts = 25.3 °C (average)

Temperature of water, T∞ = 24.5 °C (average)

Heat transfer, Q conv = H x A (Ts - T∞) (3)
= 10 W/m². °C x 0.04 m² x (25.3 °C – 24.5 °C)
= 0.32 W

<u>Heat transfer in plastic tube (6.45 m long)</u>

Given:

Convection, h = 10 W/m². °C (minimum of free convection)

Area, A = 2πrh+2πr² (4)
= 2π (0.0035) (6.45) + 2π (0.0035)²
= 0.14 m²

Temperature of Surrounding, Ts = 25.3 °C (average)

Temperature of water, T∞ = 24.5 °C (average)

Heat transfer, Qconv = H x A (Ts - T∞) (5)
= 10 W/m². °C x 0.14 m² x (25.3 °C – 24.5 °C)
= 1.12 W

<u>Wall gain load</u>

Volume of container = (π r2h) + (π r2h) (6)
= (π (0.045) ² (0.065)) + (π (0.06) ² (0.065)
= 0.00115 m³

Volume of tube = π r²h (7)
= π (0.0035) ² (6.45)
= 0.000248 m³

Total surface area = 0.04 m² + 0.14 m²
= 0.18 m²

Heat transfer through wall, Q =k x S x (T1−T2)/ΔX

where k is the thermal conductivity of water = 0.607 W/m². °C
S is the total surface area of the outer wall of both container and tube
ΔX is the thickness of insulating material.
T1 is the average of water temperature.
T2 is the average of surrounding temperature.

$Q = 0.607\ x\ 0.18\ x\ (25.3 - 24.5)/0.01 = 8.74$ W

Total heat transfer: 0.32 W + 1.12 W + 8.74 W = 10.18 W

In the realm of heater specifications, the experimental value stands at 7.67 W, while the theoretical value derived from the experiment data reaches 10.18 W. The experimental value is obtained from the heater's manual, whereas the theoretical value is computed based on the collected experimental data. The resulting percentage error between the experimental and theoretical values amounts to 24%, signifying a discrepancy of less than a quarter. Although this indicates a relatively minor difference, there remains potential for enhancements to propel the prototype towards its goal of evolving into a fully operational commercial device.

4. Conclusions

Past studies may not have placed significant emphasis on the pursuit of thermal comfort via heating systems, there persists a notable segment of individuals who harbour concerns, particularly when it comes to securing thermal comfort in frigid or cold environments. A distinct challenge emerges in the context of achieving optimal thermal conditions within aircraft, where the central control of the air conditioning system rests with the cockpit pilot. This centralized control leaves passengers with limited agency over temperature adjustments, posing a hindrance to individualized comfort management.

The obtained results indicate that the prototype successfully provides thermal comfort to passengers during winter weather conditions, with the ability to modulate temperature through clothing adjustments. Observations reveal a consistent temperature pattern between 600 seconds and 2000 seconds (approximately 10 to 30 minutes) when temperatures are below 24°C, indicating the prototype's limited impact within this range. Notably, the prototype demonstrates improved efficiency at temperatures above 22°C. Nonetheless, it is important to note that as the ambient temperature decreases, the time required to attain the desired temperature increases accordingly. Refer to ASHRAE standard reports that the most comfortable temperature for an air-conditioned room is 24.5°C, with an acceptable range of 23–26°C [29].

Significant discrepancies between experimental results and calculations were observed, primarily attributed to adverse weather conditions during testing, specifically rainy conditions, along with the utilization of less precise equipment. These challenges underscore the need for future enhancements in both experimental setup and equipment precision to ensure more accurate and reliable outcomes.

For future research endeavours, it is highly recommended that researchers delve into the intricate integration of a hydronic heating system in tandem with a cutting-edge Digital Temperature Controller featuring a highly sensitive sensor. This innovative approach aims to not only ensure accurate real-time temperature measurements but also to establish a robust validation mechanism, fostering a seamless correlation between theoretical calculations and practical observations.

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