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A case study on development of thermodynamic entropy measuring device and its implication on the human body

Selvakumar Pandiaraj a,**, Kumaresan Govindasamy b, Anand Pandey c,*, Chandrakant Sonawane c, Ali Jawad Alrubaie d, Ali Majdi e, Mohamed A. Mohamed f,g, Mustafa Musa Jaber h,i, Suresh Muthusamy j, Hitesh Panchal k

a Department of Mechanical Engineering, Kongu Engineering College (Autonomous), Perundurai, Erode, Tamil Nadu, India
b Department of Mechanical Engineering, Bannari Amman Institute of Technology (Autonomous), Sathyamangalam, Erode, Tamil Nadu, India
c Mechanical Engineering Dept, Symbiosis Institute of Technology, Symbiosis International (Deemed University), Pune, India
d Department of Medical Instrumentation Techniques Engineering, Al- Mustaqbal University College, 51001, Hilla, Iraq
e Department of Building and Construction Techniques Engineering, Al- Mustaqbal University College, 51001, Hilla, Iraq
f Department of Medical Instruments Engineering Techniques, Al-Turath University College, Baghdad, 10021, Iraq
g College of Medical Science Technologies, University of Mashreq, Baghdad, 10021, Iraq
h Department of Medical Instruments Engineering Techniques, Dijlah University College, Baghdad, 10021, Iraq
i Department of Medical Instruments Engineering Techniques, Al-Farahidi University, Baghdad, 10021, Iraq
j Department of Electronics and Communication Engineering, Kongu Engineering College (Autonomous), Perundurai, Erode, Tamil Nadu, India
k Department of Mechanical Engineering, Government Engineering College, Patan, Gujarat, India

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ABSTRACT

In the field of thermodynamics, entropy is a measure of the degree of disorder of the system considered focus. The direct measurement of entropy for microscopic systems involving molecule-level variations exists. However, for a macroscopic system, it still remains a challenge. The temperature reading is used as the primary index for understanding the quality of heat. In certain applications, the induced errors in the temperature measurement create complexity in decision making. One such case is the measurement of human body temperature for fever-like symptoms. This research aims to develop a direct entropy measuring device to indicate heat transfer for macroscopic systems. The developed device measured the mean entropy of the human body as 0.042 and 0.146 kJ/K during the daytime and nighttime, respectively. In comparison to the simulated entropy values, the measured values differed by 4% during the trials on the human body. Key decisions on macroscopic systems based on mild temperature variations can be made confidently with the measured entropy values.

* Corresponding author.
** Corresponding author.
E-mail addresses: kcselvakumarp@gmail.com (S. Pandiaraj), kumaresan@bitsathy.ac.in (K. Govindasamy), anand.pandey@sitpune.edu.in (A. Pandey), chandrakant.sonawane@sitpune.edu.in (C. Sonawane), ali.jawad@mustaqbal-college.edu.iq (A.J. Alrubaie), alimajdi@mustaqbal-college.edu.iq (A. Majdi), mohammed.mohammed@turath.edu.iq (M.A. Mohamed), mustafa.jaber@turath.edu.iq (M.M. Jaber), infostosuresh@gmail.com (S. Muthusamy), engineerhitesh2000@gmail.com (H. Panchal).

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1. Introduction

Both contact and non-contact temperature measurement devices are widely employed in various applications. The testing object and the sensor must be in thermal equilibrium to give correct contact measurement, resulting in longer response times and reading inaccuracies offset by ambient temperature. Because of their robustness and accuracy, non-contact type temperature measurement systems using infrared radiation have recently been adopted for medical and environmental monitoring applications [1]. When utilizing infrared thermometers, comparing the measured object temperatures to the ambient temperature is frequently required. To assess human body temperature, a temperature measurement system using infrared sensors was constructed [2]. The temperature measurement system included an LCD monitor and an alarm. In optical rehabilitation therapy, a real-time non-contact type human body temperature monitoring system with a response time of 0.1s was created and used [3]. Homeothermic condition refers to the state of keeping a constant internal temperature, and humans are considered homeotherms since they continuously exchange energy with their surroundings [4]. A healthy human body’s core temperature is roughly 37 °C, and if it differs by 2 °C, the person will be uncomfortable. The hypothalamus receives signals from the central nervous system via thermoreceptors throughout the body. The body’s thermal energy generation may be reduced or increased due to thermoregulatory reactions.

The second law of thermodynamics was used to calculate the rate of entropy formation in the human body [5]. Convective heat transfer effects greatly influence heat transfer rate over flat surfaces [6]. In the presence of convection, the surface temperature of the object needs more focus during the calculation of heat transfer rate [7]. The outputs of simulations of human thermal responses [8] were used as basic inputs for entropy generation relations. Entropy generation is the only thermodynamic entity that can define the entire human thermal environment by considering environmental and physiological variables [9]. Because it is highly sensitive to changing environmental conditions, entropy can be used as a marker for thermal discomfort in the human body. Boregowda et al. [10] established Maxwell relations for computing physiological entropy change. Dell’Isola et al. [11] explored the issues with using infrared thermometers and thermal imaging cameras to monitor human body temperature. The measured skin temperature did not give a clear picture of the human body’s thermal physiological status due to abrupt changes in ambient variables. The skin temperature rises during heat stress due to increased blood flow caused by peripheral vasodilatation and vice versa during cold stress [12].
develops in people sick with infectious diseases, so it’s essential to track your body temperature frequently. In non-contact type temperature measurement, measurement errors and device calibration remain challenging [13]. Although the technique began in 2003 during the severe acute respiratory syndrome (SARS) epidemic [14], scanning of skin surface temperature has increased due to the COVID-19 pandemic. Even with expert operator practices, non-contact infrared thermometry failed to identify fever. The device’s accuracy is determined by the ambient temperature and the calibration temperature range [15]. Eusner et al. [16] investigated the challenges faced by extreme environmental conditions in sensing tactile temperature responses and created a vibration-based glove with an RTD. A calorimetric model was built to determine the human body temperature; however, the results were only good under influences by human body movement, making human physiology predictions more complex [18].

The measure of a system’s thermal energy per unit temperature is entropy. It’s also known to measure a system’s molecular disorder or randomness. The total entropy of a system either increases or remains constant; it never decreases [19]. Entropy is the loss of energy available to conduct work. The energy and exergy transfer to the environment associated with radiation, convection, evaporation, and respiration might be obtained. It was also able to determine the body’s energy and exergy variations throughout time. Simulations were run for various thermoregulatory system constants. The findings showed that the thermal reaction was close to experimental responses of the human body and that the thermal response was near the minimal exergy destruction and maximum exergy efficiency [20]. Gibb’s free energy equation [21] governs the metabolic events inside the human body. The Maxwell and entropy relations are derived using Gibb’s free energy equation as a starting point.

Many researchers have invented a range of wearable technologies for monitoring human motions. Wearable devices for patients help to transfer the medical data to the hospitals monitoring system effectively [22]. Digital data processing techniques and micro-sensors play a major role in medical field for providing timely help to the patients [23]. Accuracy and interactivity are very much essential for the wearable health monitoring devices [24]. Entropy generation is an important phenomenon in heat transfer applications and it has to be studied with the help of a simulated model along with experimentation [25]. In order to study the entropy generation, mathematical modeling is another option to compliment experimental work [26]. Numerical simulation is an option that can be used for predicting the rate of heat transfer and optimizing the geometrical structures [27]. Integral and differential equations help in predicting the surface heat flux in the presence of convective boundary layer effect [28].

Entropy measurement methods are developed for microscopic system which involves molecular level studies [29]. The existing methods are suited only for gases and nano fluids as the molecular level variations are dominant in them. Novel systems for measuring thermodynamic entropy based on macroscopic approach are to be devised for intensive thermal studies. Inspired by previous studies and the need identified, an attempt was undertaken to develop an entropy measuring device. The developed device’s performance was evaluated in relation to the human body as it is coincident with present day’s problem.

2. System design of entropy measuring device

2.1. Entropy calculations

It was decided to simulate the entropy values for known body temperatures under varying ambient conditions. An earlier study by a number of researchers established that human life processes are thermodynamic in nature and that thermodynamic law can be utilized to simulate human physiology [17]. As per the second law of thermodynamics, specific entropy relation is given by Eq. (1).

\[
(\Delta S) = C_p \ln \left( \frac{T_2}{T_1} \right)
\]

Where \(T_1\) is the ambient temperature, \(T_2\) is the body temperature, and \(C_p\) is the specific heat of the body.

The specific heat of human skin, muscles, and organs varied between 3.2 and 3.9 kJ/K [23]. In this research, a mean value of 3.55 kJ/K was considered for change in entropy calculation. Assuming an average daytime temperature of 35 °C and a nighttime temperature of 26 °C, the entropy values were simulated and presented in Table 1. These simulated values helped set the inbuilt values and modes in the entropy measuring device.

To further improve measurement accuracy, entropy variations resulting from blood pressure, heart rate, and skin temperature were studied. Maxwell’s thermodynamic relations [10] were used by some researchers who helped in this investigation.

The exactness rule derives Maxwell relations from property relations of thermodynamic potentials. There are four thermodynamic potentials for a simple blood pressure-based human physiological subsystem, and they are expressed in Eqs. (2)–(5).

\[
\text{Internal energy can be expressed as } dU_{BP} = S \cdot TdS_{BP} - BP \cdot dHR
\]
Enthalpy can be expressed as
\[
\frac{dH}{BP} = S \cdot \frac{dS}{BP} + HR \frac{dBP}{BP}
\] (3)

Helmholtz function can be expressed as
\[
\frac{dF}{BP} = BP \frac{dHR}{BP} - S_{BP} \frac{dS}{BP}.
\] (4)

Gibbs function can be expressed as
\[
\frac{dG}{BP} = HR \frac{dBP}{BP} - S_{BP} \frac{dS}{BP}.
\] (5)

The following Maxwell relations (Eqs. (6)–(9)) are obtained by invoking the exactness condition to the above four property relations:

\[
\frac{\partial S}{\partial HR} \bigg|_{BP} = - \frac{\partial BP}{\partial S_{BP}} \bigg|_{HR}
\] (6)

\[
\frac{\partial S}{\partial BP} \bigg|_{ST} = \frac{\partial HR}{\partial S_{BP}} \bigg|_{BP}
\] (7)

\[
\frac{\partial S}{\partial HR} \bigg|_{BP} = \frac{\partial S_{BP}}{\partial HR} \bigg|_{BP}
\] (8)

\[
\frac{\partial HR}{\partial S} \bigg|_{ST} = - \frac{\partial S_{BP}}{\partial BP} \bigg|_{ST}
\] (9)

The above-mentioned partial derivatives are approximated to form a modified set of Maxwell relations that are used in the present experimental study to compute the physiological entropy change:

\[
\frac{\Delta S}{\Delta HR} \bigg|_{BP} = - \frac{\Delta BP}{\Delta S_{BP}} \bigg|_{HR}
\] (10)

\[
\frac{\Delta S}{\Delta BP} \bigg|_{ST} = \frac{\Delta HR}{\Delta S_{BP}} \bigg|_{BP}
\] (11)

\[
\frac{\Delta S}{\Delta HR} \bigg|_{BP} = \frac{\Delta S_{BP}}{\Delta HR} \bigg|_{BP}
\] (12)
Any of the above relations (Eq. (10)–(13)) can be used to quantify the human physiological entropy change $\Delta S_{BP}$. Using the Helmholtz function-based thermodynamic potential [10], the physiological entropy change resulting from changes in blood pressure (BP), heart rate (HR), and skin temperature (ST) can be written as in Eq. (14).

$$\Delta S_{BP} = \Delta BP \times \left( \frac{\Delta HR}{\Delta ST} \right)$$

This change in entropy due to blood pressure calculated using BP, HR, and ST was correlated with the change in entropy. The calculated entropy values were well within the range of simulated values, and the device development started.

2.2. Components used

2.2.1. NodeMCU

Because of its easy compatibility with IoT-based applications, NodeMCU version 0.9, an open-source Lua-based firmware, was
Table 4
Specifications of display.

| Specifications             | Value   |
|----------------------------|---------|
| Number of characters       | 16      |
| Number of lines            | 2       |
| Type of character and cursor| Dot Matrix |
| MPU Interface              | 8-bit   |

Fig. 4. Alarm.

Table 5
Specifications of alarm.

| Specifications       | Value       |
|----------------------|-------------|
| Operating voltage    | 3.3V–5V     |
| PCB Dimension        | 29 (L) x 14(W) x 12(H) mm |
| Frequency            | 2500 Hz     |

Fig. 5. Push-button.
chosen for this project. Table 2 contains the exact specs for the microcontroller unit depicted in Fig. 1.

2.2.2. Contactless temperature sensor

The infrared (IR) temperature sensor works by using light detectors to capture the infrared energy released by the object. An infrared sensor, like the one illustrated in Fig. 2, can detect motion and measure the heat of an item. Any object’s radiated infrared radiation is proportional to its temperature. The temperature of the object was correctly read using a converted electrical signal. The detailed specification of the temperature sensor is presented in Table 3.

2.2.3. Display unit

An LCD (Liquid Crystal Display) screen is an electronic display used in various ways. Fig. 3 shows a 16 × 2 LCD unit displaying 16 characters per line. The exact specification of the display unit used in this study is shown in Table 4.

2.2.4. Alarm

A buzzer, often known as a beeper, is a mechanical, electromechanical, or piezoelectric audio signaling device. Alarm clocks, timers, and other devices commonly use buzzers and beepers. For this study, an alarm (shown in Fig. 4) with a frequency of 2500 Hz was used, and details are listed in Table 5. This alarm will beep when the body’s entropy surpasses the limiting value.

2.2.5. Pushbutton

A push-button is a simple switch mechanism used to turn something on or off in a machine or process. In this experiment, a single pole single throw (SPST) type push button (shown in Fig. 5) was used. Table 6 lists the specs for the SPST push button.

2.3. Working

The separate components were put together and tested, as shown in Fig. 6. The newly created device’s operation was comparable to an existing infrared thermometer. When the push button is pressed, the temperature sensor detects the body’s temperature and transmits the information to the nodeMCU. The infrared sensor can detect the temperature of objects within a 20-cm range. To convert the temperature value to entropy, the nodeMCU is coded using the mathematical relations outlined in section 2.1.

2.4. Experimentation on the human body

The instrument is set up to calculate the object’s entropy using Maxwell’s thermodynamic relations. This study aims to determine the entropy of the human body, which is a pressing requirement due to the widespread development of covid-19. The entropy range of the human body was determined under various ambient temperature settings. Maxwell’s mathematical relations were adapted to human body situations with the help of existing literature [31]. In order to detect the entropy, the nodeMCU was adjusted with the necessary input and reference values. The major variable that determines the observed entropy value is the ambient temperature. Along with the sensed temperature value, the measured result was displayed. The actual heat dissipated by the human body is the measured entropy. With a recognized entropy range, a person with a fever but no high-temperature indication can be easily identified. The entropy data were calibrated and sent to the nodeMCU with reference to varying ambient temperature conditions. The alarm will

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Table 6
Specifications of alarm.

| Material       | Plastic          |
|----------------|------------------|
| Voltage        | 125V             |
| Current        | 3 A              |
| Type           | Single Pole Single Throw (SPST) |

Fig. 6. The assembled setup.
beep if the measured entropy value is greater than the calibrated entropy value. This technology is also easily handled by people with minimal skill levels. It is equipped with a blood pressure sensor and a heart rate sensor, which will aid in the comprehension of an unconscious human’s entropy at medical facilities. It would be possible to do detailed research on using this device in operating rooms and intensive care units to establish a patient’s state of consciousness while being treated with anesthesia.

3. Result and discussion

The trials were carried out on a healthy person with a midday ambient temperature ranging between 33.1 °C and 33.4 °C. Table 7 shows the entropy values that the gadget recorded. The data clearly show that the entropy value is dependent on both body temperature and ambient temperature. The ambient temperature significantly impacts the body temperature recorded using a commercial infrared thermometer. In April 2021, similar experimental trials were conducted at about 9:00 p.m. The room temperature ranged from 24.7 °C to 25 °C. Table 8 shows that there are significant differences in entropy levels. During the day and night, the human body showed varying entropy values at the same temperature. Because entropy is the heat energy released by the human body due to metabolic activity, it can be used to detect a fever patient. Because it considers both the ambient and body temperatures, this entropy measurement device can provide more accurate results.
Fig. 8. Influence of ambient temperature on the change in entropy during nighttime.

Fig. 9a. Change in entropy during varying time.

Fig. 9b. Sample readings during daytime.
According to the results, the uncertainty stated with entropy values was only 0.005 at the end of 10 trials. The measured entropy values ranged from 0.040 to 0.045 kJ/K during the daytime trials. The entropy was strongly influenced by the ambient temperature, even with minor fluctuations in body temperature, as seen in Fig. 7. The results from the nighttime trials confirmed the impact of ambient temperature on entropy measurement, as shown in Fig. 8. The environment-induced error during determining human body temperature with the help of an infrared thermometer is also clearly noticed in Table 8 values. The recorded body temperature by an infrared sensor is the same irrespective of ambient temperature, which is not convincing for the clinical person to decide on fever symptoms. The number of errors in detecting fever patients can be reduced by changing the entropy levels. In Fig. 9a, the change in entropy values measured during the day and night were compared. Because of the low ambient temperature, entropy values are higher at night than during the day. The measured entropy levels were low relative to the simulated values during daytime trials; however, this was reversed during nighttime trials. The average discrepancy between simulated and measured entropy levels in the night trials was lower compared to the day trials.

These findings demonstrate that entropy change can be used to examine the human body’s health for fever-like symptoms, as it showed huge differences with little changes in body temperature. From Fig. 7 it was clear that the mild variations in ambient temperature had great impact on entropy values. The body temperature measured by the instrument does not show significant variations across the 10 trials. The entropy values varied between 0.04 and 0.045 during the daytime trials.

The images of recorded sample readings during daytime and nighttime can be viewed in Fig. 9b and Fig. 9c. For body temperature 37.4 °C, in daytime the entropy value is recorded as 0.042 kJ/K and for the same temperature in nighttime, the entropy value is found

![Fig. 9c. Sample readings during nighttime.](image)

![Fig. 10a. Simulated entropy Vs. Measured entropy (daytime values).](image)
to be 0.150 kJ/K. The values of entropy depend on the ambient temperature too. When infrared thermometer is used for measuring the human body temperature, the instrument will be showing the same value irrespective of the internal body condition. The entropy based device will account the ambient temperature and shows the actual energy level of the body. The surface temperature may vary due to surrounding convectional effects. Errors are induced in the present day infrared thermometers and detection of feverish person with the help of such device is problem.

During the day, the average variation between simulated and observed entropy levels was 9.22%, but the deviation was just 1.21% at night.

The average discrepancy between simulated entropy values and measured entropy values was less than 5% in the 10 trials, as shown in Fig. 10a and b. Furthermore, both the measured and simulated values have linear variations, indicating that the instrumental error is relatively low.

This entropy measuring device may be further developed by adding a blood pressure sensor and a heart rate sensor which can offer more precise entropy readings. The precise entropy values will be helpful in the clinical diagnosis of a variety of fever-related disorders.

4. Conclusion

In the realm of thermal studies, entropy and exergy are two significant keywords. When computed or monitored accurately, entropy can provide a wealth of information. This study attempted to measure entropy in one way or another. Using example readings, the mistakes caused by an infrared thermometer in measuring the human body temperature due to ambient temperature were discussed. The average entropy of a healthy human body was discovered to be 0.042 and 0.146 kJ/K during the day and night, respectively, using the developed entropy measurement equipment. The measured entropy levels differed by 4% compared to the simulated values. During the daytime, the simulated and observed entropy levels varied by 9.22%, whereas in the night time, but the variation was just 1.21%.

Author statements

Selvakumar Pandiaraj, Kumaresan Govindasamy, Anand Pandey, Chandrakant Sonawane - conceptualization, Methodology, Experimentation.
Ali Jawad Alrubaie, Ali Majdi, Mohamed A. Mohamed – Formal analysis.
Mustafa Musa Jaber – supervision.
Ali Jawad Alrubaie, Suresh Muthusamy, Anand pandey- Funding acquisition, Project administration.
Hitesh panchal, - Proofing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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