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Temperature Distribution in a Convection Heat Transfer Medium

A. J. Ujam[1]
M. Ugwu[2]
I. Nwaru[2]
C.W Ezema[1]
S. N Ani[1]

[1]Department of Mechanical Engineering, Madonna University, Nigeria, Akpugo
[2]Department of Mechanical Engineering, Caritas University, Amorji-Nike, Enugu, Nigeria

Abstract

This paper focuses on the demonstration of spatial temperature distribution in a convective heat transfer module using a 3-D EDIBON Physics apparatus. Particularly, the work demonstrates the temperature distribution in a module having two focuses (barrels) containing hot and cold water with differing temperatures. The basic equipment in the work were: Aluminum based 3-Robot Arm with scanning area of 300x550mm and depth of 250mm; control interface; control software; temperature sensor; computer set; small barrel Cu walls with boiling rings and thermostatic control (hot focal point); small barrel Cu walls (cold focal point). The hot and cold focuses were kept at a distance of 280mm. The water in the hot focus was kept at a temperature of 32°C using a boiler inserted in the barrel while the water in the cold barrel was infused with ice block that brought the temperature to 7.7°C. The temperatures were measured using a digital temperature sensor and also read from the monitor of the interface computer set. The three coordinates of X, Y and Z were set at different values of 20, 30 and 40mm respectively indicating their relative positions. The differential positions on the Robot Arm were moved and the values of the temperature and volume were displayed on the interface monitor and recorded. The experiment was repeated for an increase in water temperature in the hot focus by 5°C while keeping the water in the cold focus at 6.7°C. The temperatures before and after the sweeping of the Robot Arm were displayed and recorded. The experiment was repeated for successive positioning of the Robot Arm and varying the temperature of the hot focus by 5°C (while keeping the distance between the hot and cold focuses constant at 280mm), and the readings of the temperature and volume read on the interface monitor. The temperature of the cold focus was kept low (between 3°C and 10°C throughout the experimental trials. Results show increase in temperature with successive positioning (increases) of the Robot Arm up to a peak value of 26.80°C and subsequent decrease. The experiment was conducted nine times and the average temperature value obtained and recorded after every test as follows: 24.26°C, 24.77°C, 25.03°C, 25.83°C, 25.66°C, 26.3°C, 26.73°C, 26.54°C and 26.80°C respectively. This work shows that heat is transferred when there is temperature gradient between two media and the quantity of heat transferred is a function of the temperature difference between the two media. It also indicates that temperatures are distributed in accordance with the positioning (distance) of the Robot Arm from the base.

Keywords: Temperature, Heat Transfer, Convection, Water, Control, Distribution

1.0 Introduction:

Convection heat transfer is one of the key concepts in thermodynamics, and it plays a crucial role in many of our day-to-day processes. Convection heat transfer appears in many forms in our everyday world: from boiling water to the heat exchangers in heating systems. This phenomenon gives one more way to comprehend basic physics and get insight into many household devices and natural processes.

Convection (convective heat transfer) is the transport of thermal energy between a surface and a moving fluid via the combined action of molecular diffusion (conduction within the fluid) and bulk fluid motion (advection). It is commonly categorized as natural (free) convection, driven by buoyancy forces due to temperature-induced density gradients, and forced convection, driven by external means such as fans, pumps, or pressure gradients (Bejan [15]; Çengel & Ghajar [16] ; Incropera et al. [1]. The literature underscores the complexity of temperature distribution in heat transfer, influenced by material properties, system geometry, and boundary conditions. Theoretical models, such as Newton's law of cooling, provide a framework for prediction, but empirical validation is critical. Experimental tools like the EDIBON 3D Physics apparatus [17] enable precise measurements, bridging theory and practice. Gaps remain in understanding how material selection and system design affect temperature distribution under transient conditions, which this study aims to address.

The computer controlled three dimensional (3D) Physics unit, "EFAC" developed by EDIBON, is an advanced educational apparatus designed to facilitate practical experimentation across various physics domains, including electrical, magnetism, mechanics, thermodynamics, optics. This versatile system enables students and educators to conduct hand-on experiments, enhancing the comprehension of complex physical phenomena. Heat transfer is a fundamental discipline in thermal engineering, focusing on the generation, use, conversion, and exchange of thermal energy between physical systems. It encompasses three primary mechanisms: conduction, convection, and radiation, often occurring simultaneously in practical applications of Heat Transfer. Understanding temperature distribution within these mechanisms is critical for designing efficient thermal systems, such as heat exchangers, electronic cooling systems, and industrial processes. The study, therefore, explores temperature distribution in convectional heat transfer, utilizing the EDIBON 3D Physics apparatus to conduct controlled experiments. The apparatus allows precise measurement and visualization of temperature gradients, providing insights into how heat propagates through different materials and configurations.

2.0 Literature Review

Historically, pioneers like Benjamin Thompson (Count Rumford) conducted early experiments on thermal convection, laying the groundwork for modern heat transfer studies [1]. These foundational works highlighted the importance of fluid properties and system geometry in determining temperature distribution. Today, advancements in experimental tools, such as the EDIBON 3D Physics system, enable detailed analysis of heat transfer phenomena, making it possible to validate theoretical models with empirical data.

Khalifa [2] conducted a comprehensive review of natural convection heat transfer coefficients for two- and three-dimensional enclosures, showing discrepancies of up to a factor of five for vertical surfaces and eight for downward-facing horizontal surfaces between various empirical correlations. These variations emphasized the sensitivity of convective performance to surface orientation and boundary conditions. Tou et al [3] experimentally studied natural convection in cubic enclosures with non-uniform heating, observing complex flow recirculation patterns and temperature gradients that deviated from two-dimensional predictions. Frederick and Moraga [4] extended this by using three-dimensional numerical simulations to capture the effect of wall thickness and conduction on internal temperature fields. Zhang et al [5] investigated heat transfer in porous ceramic foams under reciprocating airflow, demonstrating that internal convection pathways can produce highly non-uniform temperature distributions, a finding relevant to complex geometries like those in 3D apparatus blocks.

Hetsroni et al [6]. (2018) reviewed advancements in miniature thermocouples and optical sensors for multipoint temperature measurement. Urban et al [7]. (2021), using Particle Image Velocimetry (PIV) and synchronized thermocouple arrays, demonstrated that turbulent natural convection can form large-scale coherent structures ("superstructures") that dominate spatial temperature variation. Moller et al [8]. (2022) showed that boundary condition type (constant temperature vs. constant heat flux) affects local temperature fluctuations, even when average heat transfer rates remain similar — reinforcing the need for localized measurements such as those provided by EDIBON's embedded sensors.

Huang et al [9] explored vertical plates with discrete heating elements, showing that localized heating strongly modifies natural convection boundary layers, leading to non-standard Nusselt number distributions. Their results stressed the importance of understanding spatial non-uniformity in convection. Ahmed et al [10] studied mixed convection over flat plates with varying surface roughness, reporting that turbulence intensity and roughness height significantly altered local heat transfer coefficients. Soni and Joshi [11] used infrared thermography to analyze forced convection over stepped surfaces, highlighting how geometry-driven flow separation alters temperature fields. These findings suggest that even in controlled environments, small changes in surface condition can lead to measurable differences in temperature distribution a factor directly testable with EDIBON's adjustable convection settings.

Kuznetsov and Sheremet [12] numerically modeled turbulent natural convection in enclosures with finite-thickness conducting walls, demonstrating that internal conduction significantly affects fluid temperature fields. Alvarado et al [13] experimentally examined aluminum foam blocks in cross flow, finding that steady-state and transient regimes yielded different effective thermal conductivities due to combined conduction and convection effects. Li et al [14] combined CFD and experimental work to study electronics cooling, confirming that solid–fluid coupling can cause local hot spots not predicted by simplified models. This conjugate interaction is precisely what the EDIBON 3D apparatus is designed to explore, as it allows measurement of conduction inside the block and convection at the surface simultaneously.

3.0 Materials and Methods

3.1 Materials

a. Temperature sensor:
b. Experiments deposit (fluids):
c. Small barrel Cu walls with a resistor within (hot focus):
d. Small barrel Cu walls (cold focus): essentially the chilled counterpart to the heated version
e. 3-Dimension motor arms: 3-dimension motor arms are articulated mechanical arms designed to move and position objects precisely along three spatial axes X, Y, and Z.
f. Computer-Controlled Interface: A computer-controlled interface is the bridge between human instruction and machine actions
g. Boiler
h. Thermostat (adjust temperature in the hot focal point)

3.2 **Modular design**

The EFAC system comprises a base frame and a robotic arm, to which various study sets can be attached. This modularity allows users to tailor the apparatus to specific educational needs, focusing on a particular physics field.

3.2.1 Base structure and Robots

Anodized aluminum structure. Metallic element in the steel.

Cartesian robots controlled by 3 motors.

The X, Y, and Z axes.

Support for the sensors.

Robot's arm, computer controlled, with a sweeping area.

Electronic box for the motors multiplexing. This box is controlled by

Programmable Logic Controller (PLC) allocated into the controlled interface box.

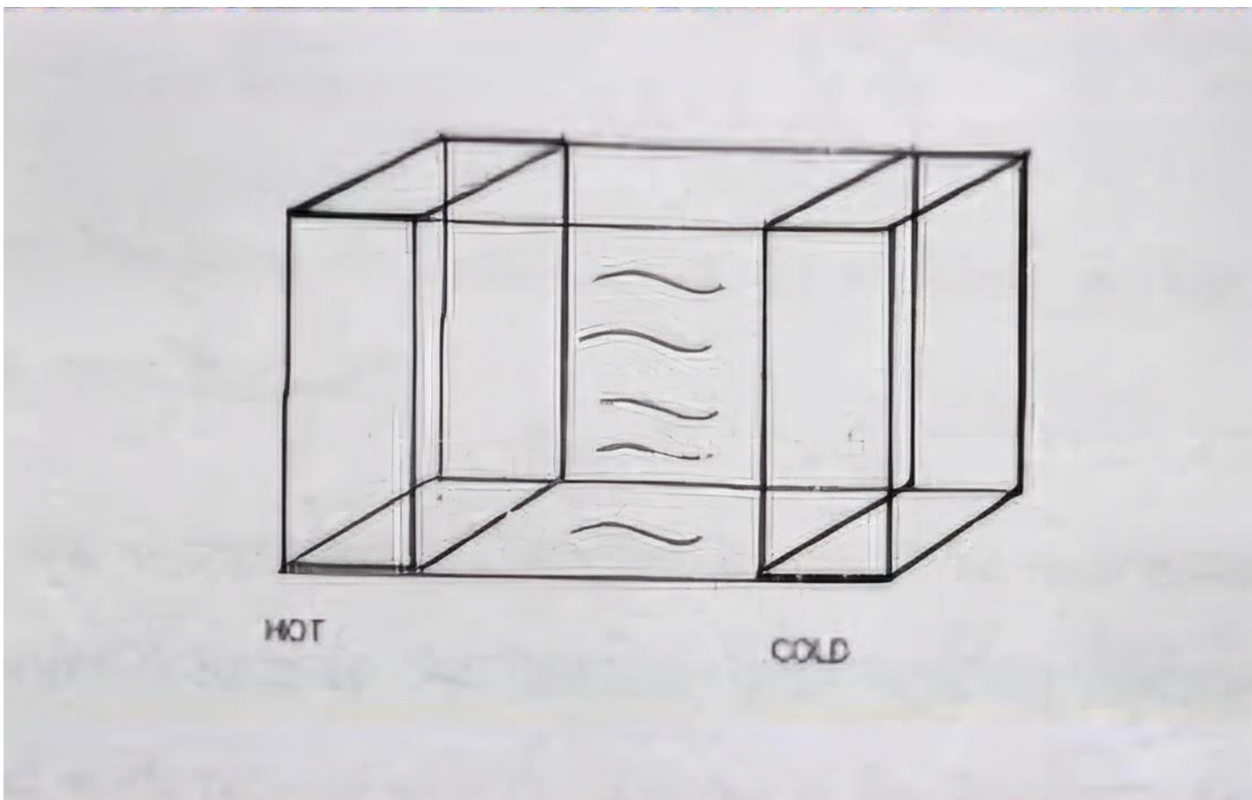

Fig. 1: Barrel wall

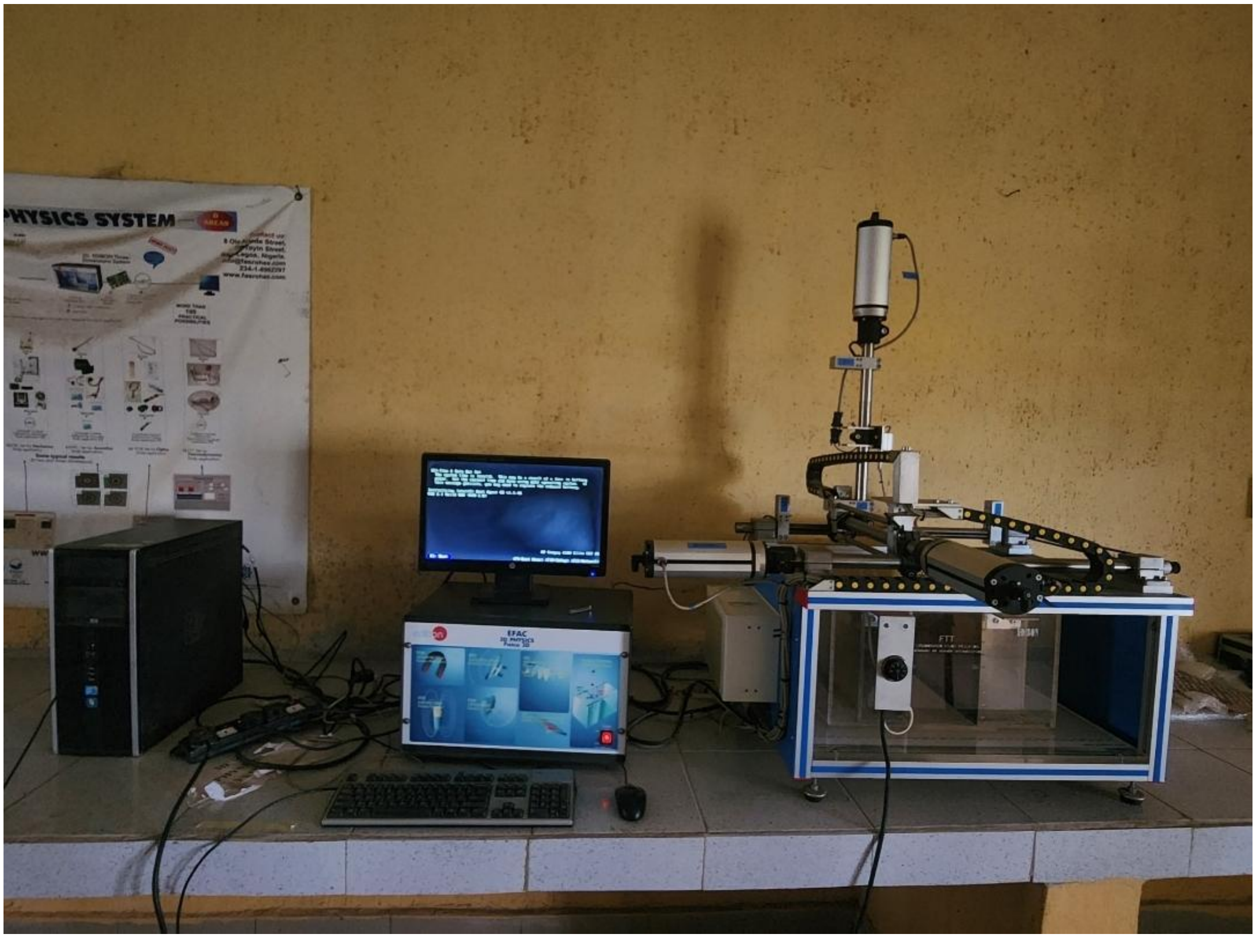

Fig. 2: 3-D EDIBON Physics Apparatus set up.

3.3 Detailed Experimental Procedure

1. The apparatus was set up with all sensors, probes and components correctly connected and calibrated.
2. The Computer system was put on with the software configured to select the specific experiment to be carried out.
3. The barrel corresponding to the cold focus was filled with a mixture of water and ice, and the hot focus totally with water.
4. The distance between the two focuses was measured and recorded
5. The resistor was switched on and the temperature of the hot focus was regulated with the thermostat at a fixed power for the water inside to reach 32.0°C. This temperature was recorded with the digital temperature sensor.
6. The cold focus being infused with ice block was kept at a temperature 7.7°C
7. The point coordinates X, Y and Z were fixed at 20, 30, and 40mm respectively.
8. The robotic arms were moved across planes to the coordinates for the sweep.
9. The spatial temperatures before and after the sweep were recorded.
10. Thee experiment was repeated for successive positioning of the Robot Arm and varying the temperature of the hot focus by 5^{o}C (while keeping the distance between the hot and cold focuses constant at 280mm), and the readings of the temperature and volume read on the interface monitor. The temperature of the cold focus was kept low (between 3^{o}C and 10^{o}C throughout the experimental trials

Fig. 3: 3-D Physics Control Interface System

4.0 Results and Analysis

Sets of values were recorded after the experiments

4.1 Test Results

Initial Reading

Hot focus at 32.0°c

Cold focus at 7.7°c

Xx at 280mm

Point coordinates:

For test 1: X=20, Y=30, Z=40

For test 2: X=20, Y=40, Z=50

For test 3: X=20, Y=50, Z=60

For test 4: X=20, Y=60, Z=70

For test 5: X=20, Y=70, Z=80

For test 6: X=20, Y=80, Z=90

For test 7: X=20, Y=90, Z=100

For test 8: X=20, Y=100, Z=110

For test 9: X=20 Y=110, Z=120

Result for trial.

The result for the temperature distribution is presented in table below:

Table 1: Spatial distribution of Coordinates.

S/N	Tc(°c)	T_h(°c)	T_b(°c)	T_a(°c)	X(mm)	Y(mm)	Z(mm)	Vx(mm)	Vy(mm)	Vz(mm)
Test 1	7.7	32.0	23.26	25.26	273	250	168	50.0	10.0	0
Test 2	6.7	37.8	24.28	25.25	273	250	168	50.0	10.0	0
Test 3	5.4	44.4	24.32	25.75	273	250	168	50.0	20.0	0
Test 4	5.0	50.0	25.29	26.37	273	250	168	50.0	25.0	0
Test 5	3.7	55.6	25.32	26.01	273	250	168	50.0	27.0	0
Test 6	4.7	60.0	25.91	26.69	273	250	168	50.0	30.0	0
Test 7	5.5	65.0	26.40	27.07	273	250	168	50.0	20.0	0
Test 8	5.3	70.2	26.21	26.88	273	250	168	50.0	15.0	0
Test 9	5.2	75.1	26.75	26.86	273	250	168	50.0	10.0	0

Where:

T_c = temperature of cold focus

T_h = temperature of hot focus

T_b = temperature before sweep

Ta = temperature after sweep

X = point distance along x axis

Y = point distance along y axis

Z = point distance along z axis

Vx = volume along x axis

Vy = volume along y axis

Vz = volume along z axis

T_{avg} = temperature average

Table 2: Average Temperature Readings

T_b(°C)	Ta(°C)	T_{avg}(°C)
23.26	25.26	24.26
24.28	25.25	24.77
24.32	25.75	25.03
25.29	26.37	25.83
25.32	26.01	25.66
25.91	26.69	26.3
26.40	27.07	26.73
26.21	26.88	26.54
26.75	26.86	26.80

Table 3: Point co-ordinate and Average Temperature

X	Y	Z	Tavg(°C)
20	30	40	24.26
20	40	50	24.77
20	50	60	25.03
20	60	70	25.83
20	70	80	25.66
20	80	90	26.3
20	90	100	26.73
20	100	110	26.54
20	110	120	26.80

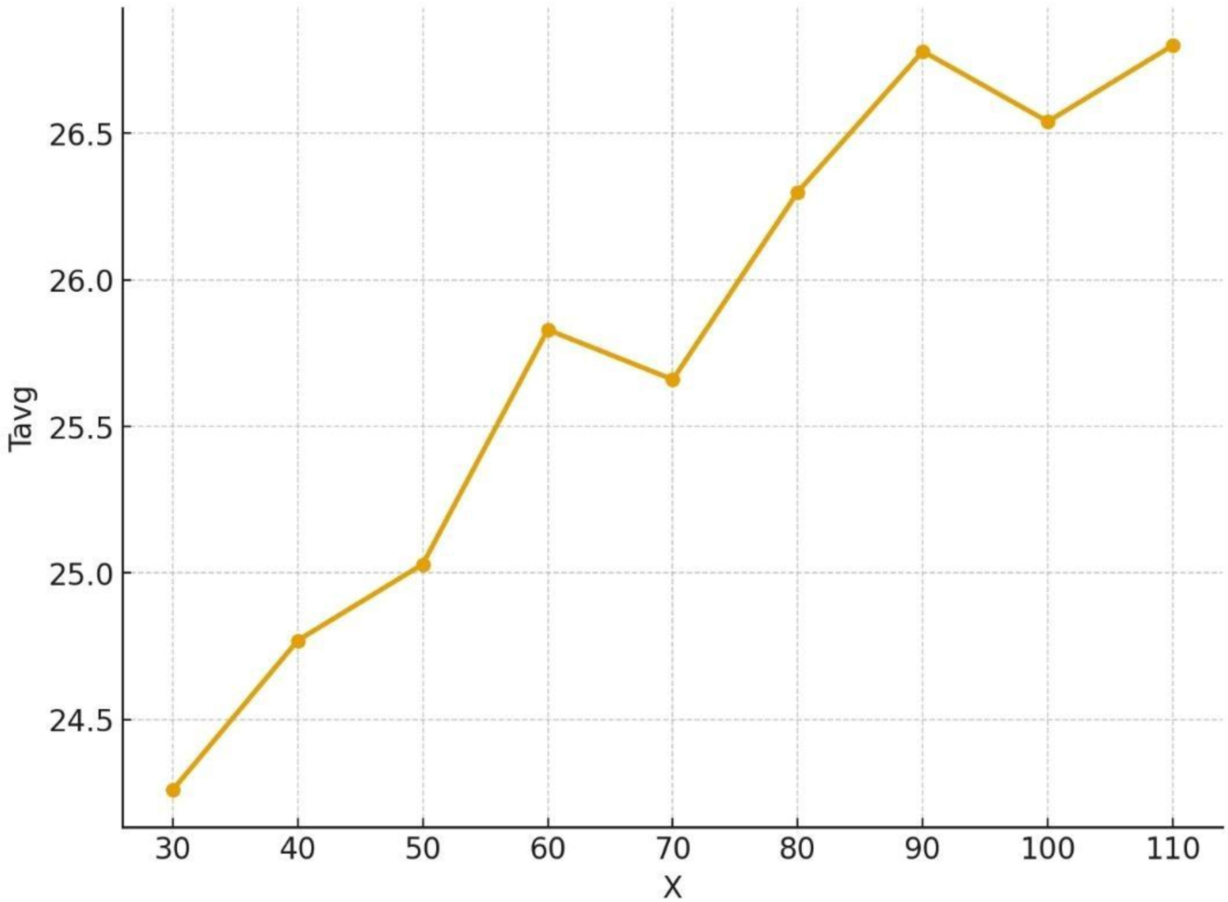

Fig 4: Plot of Temperature versus Distance

X is distance along Y-axis (mm) and T_{avg} (^oC) is the average temperature

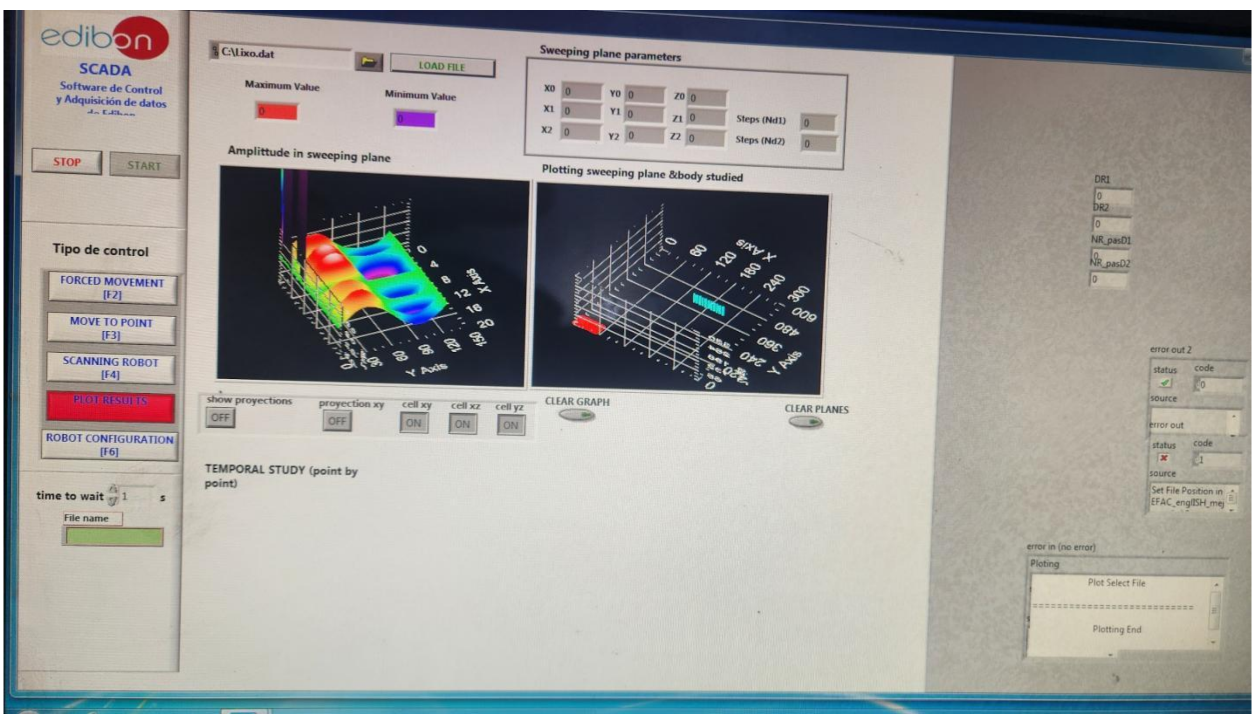

Fig. 5 Sweeping Plane for Test 1

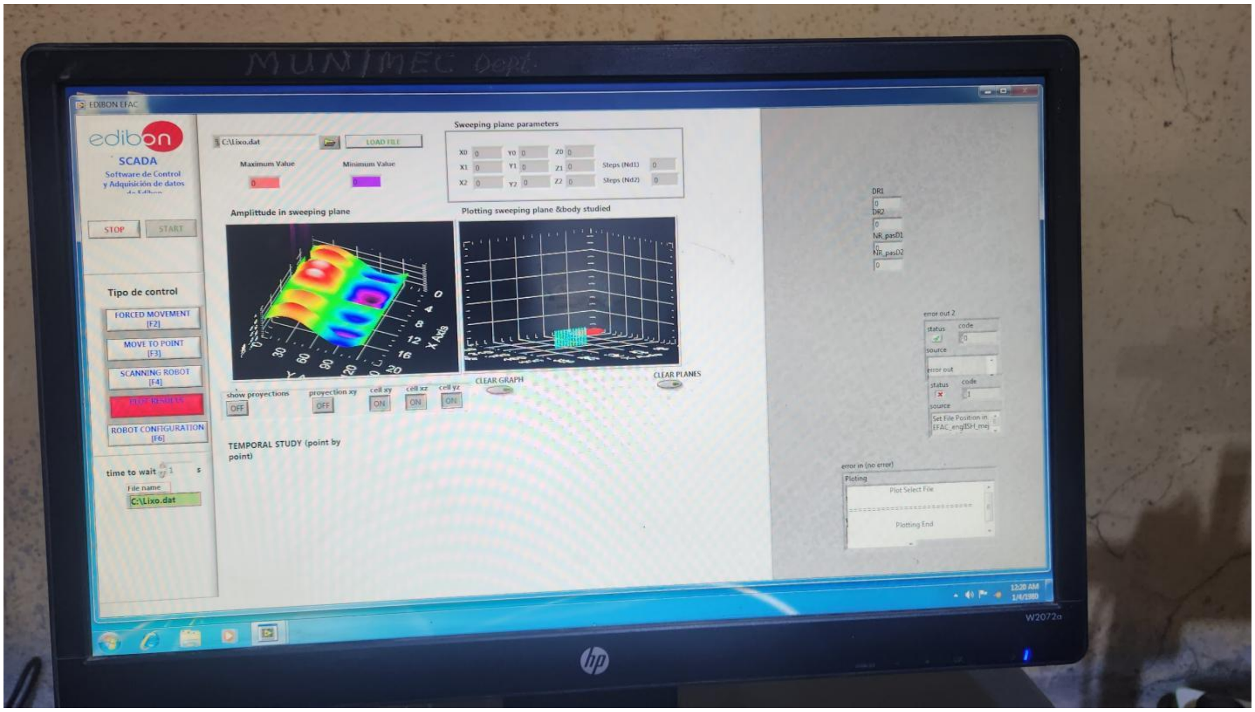

Fig. 6 Sweeping Plane for Test 2

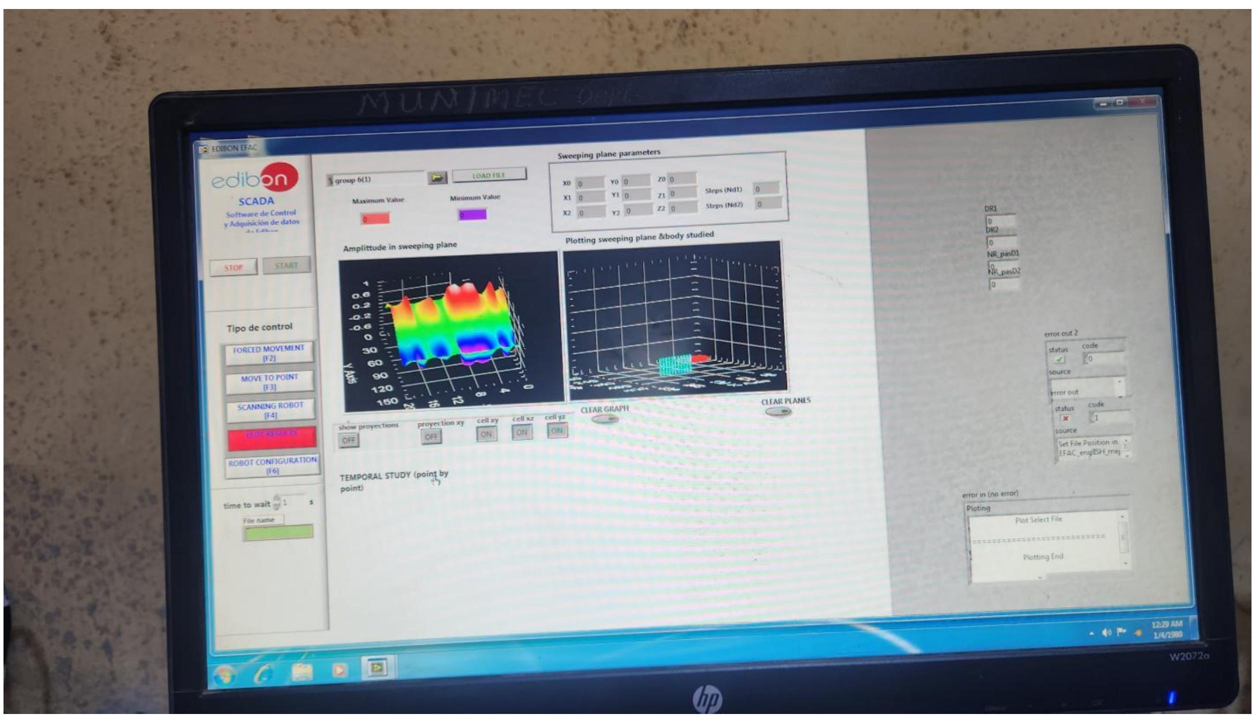

Fig. 7 Sweeping Plane for Test 3

Fig. 8 Sweeping Plane for Test 4

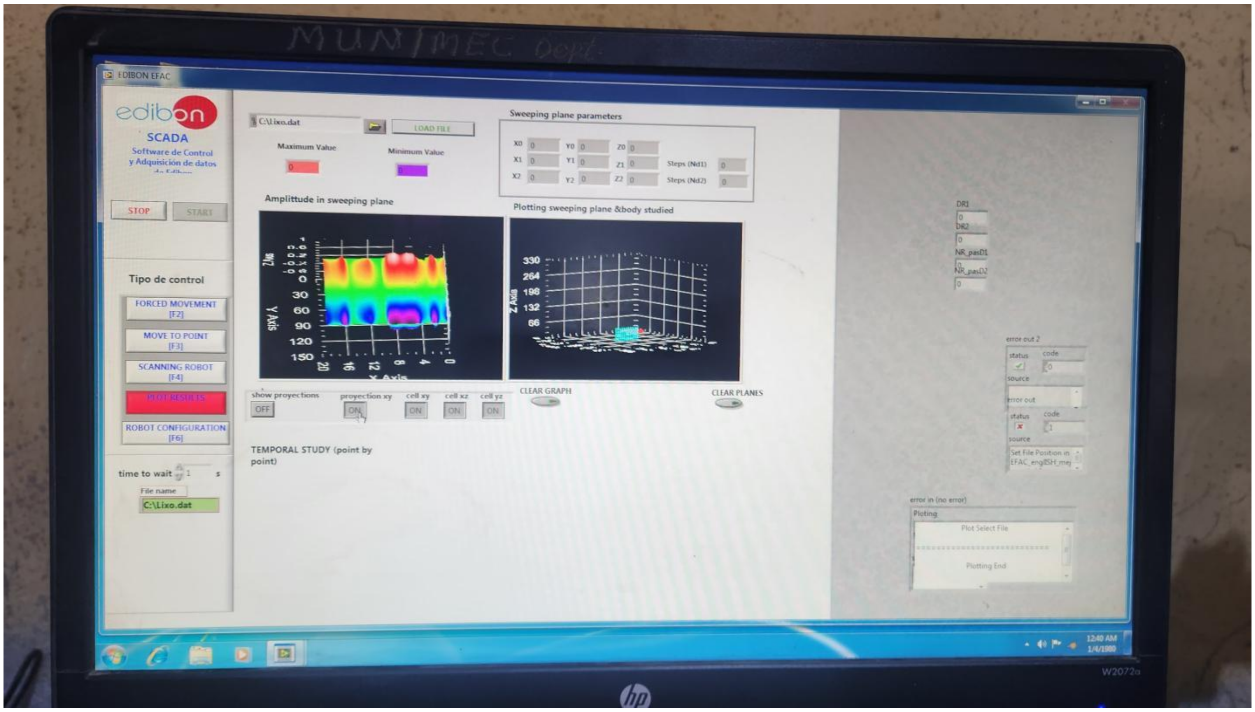

Fig. 9 Sweeping Plane for Test 5

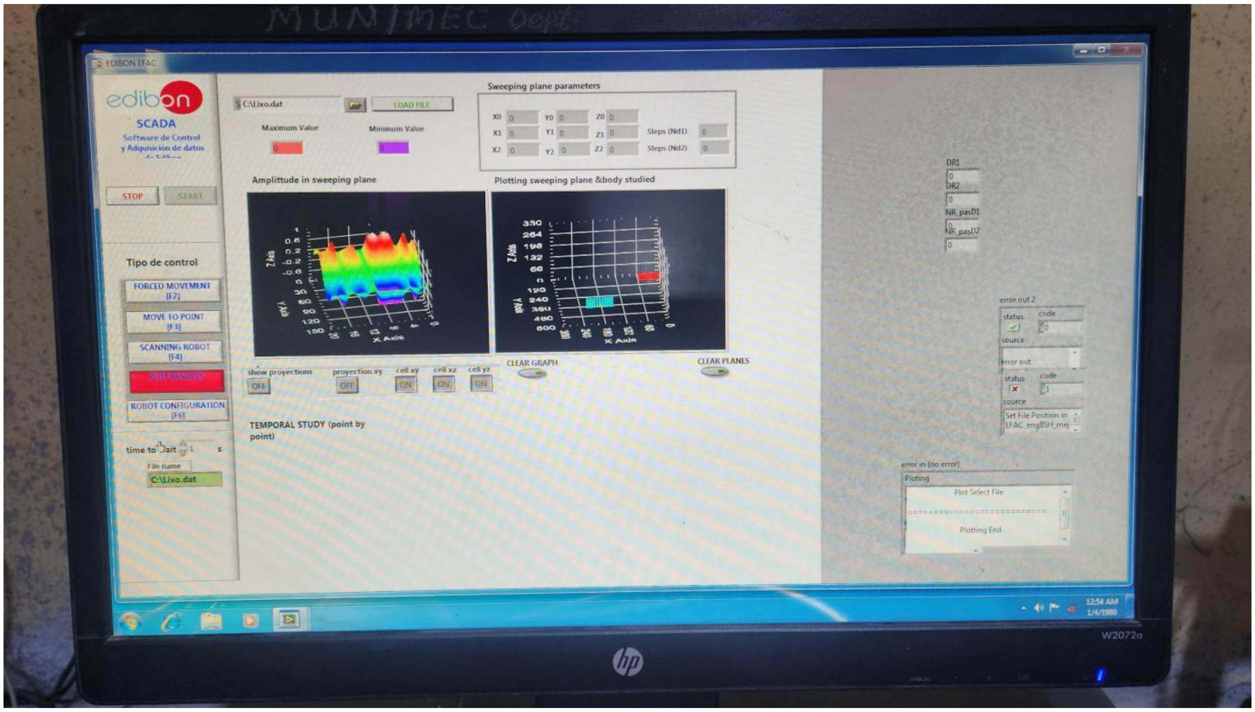

Fig. 10. Sweeping Plane for Test 6

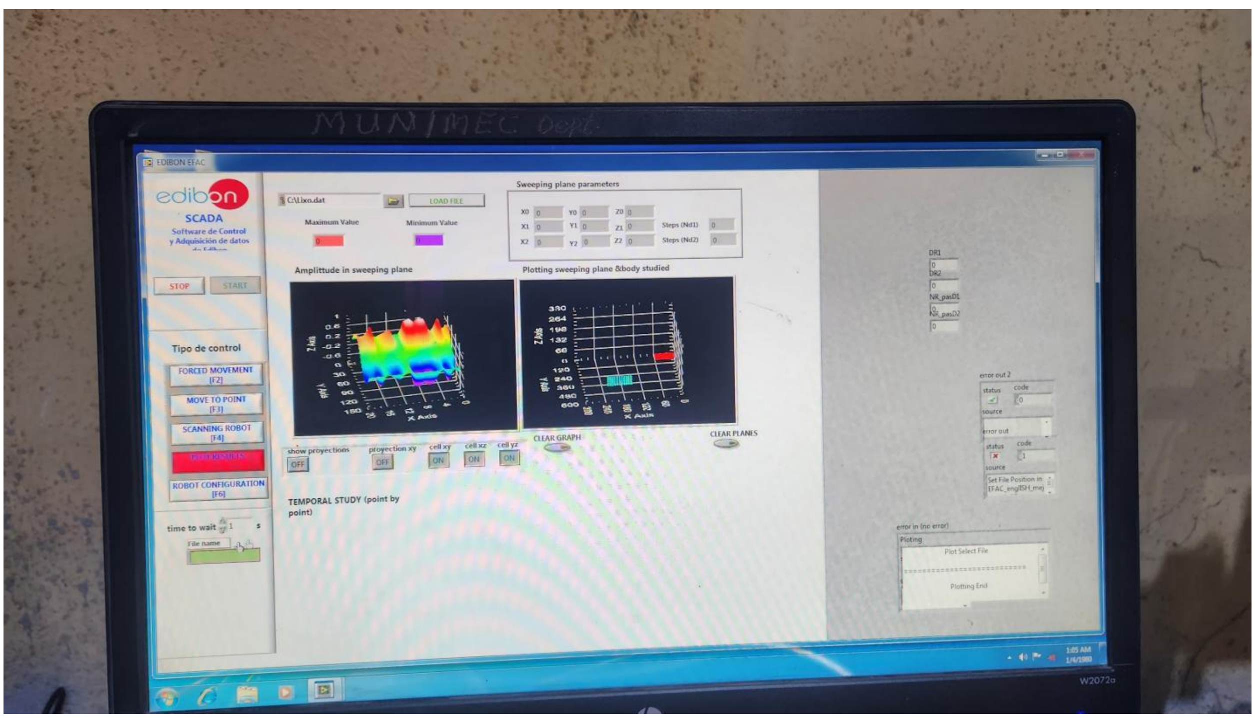

Fig. 11 Sweeping Plane for Test 7

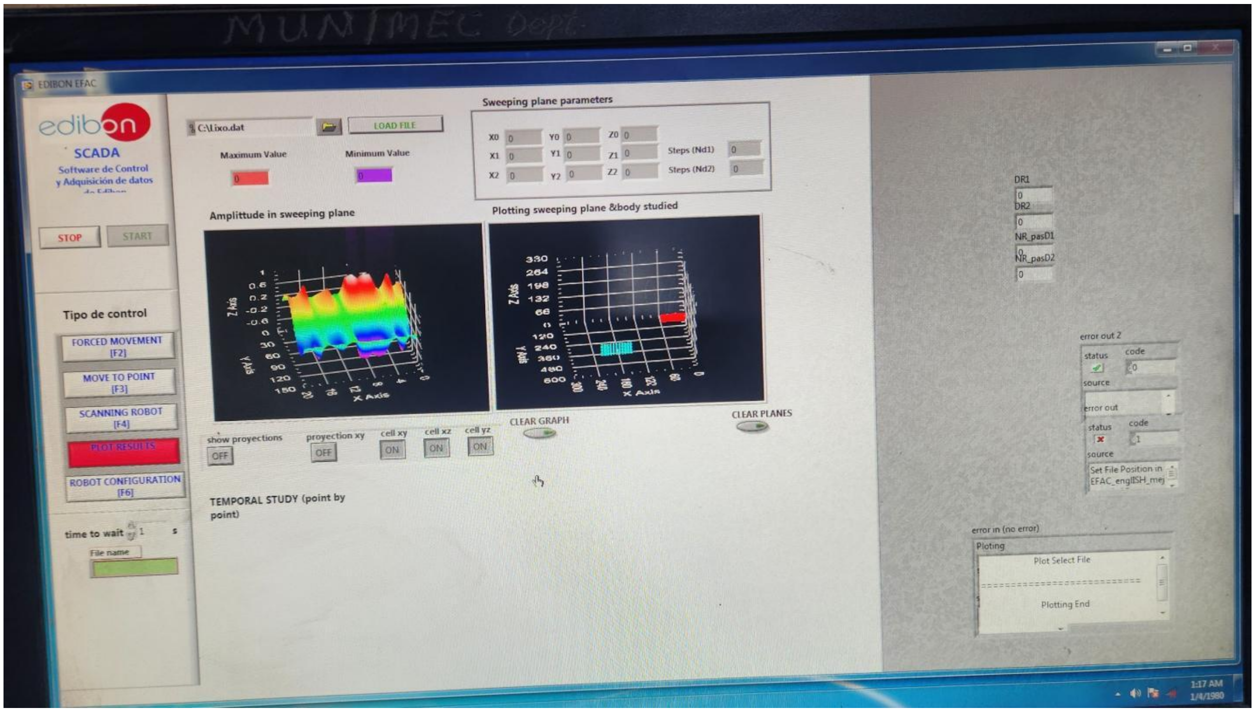

Fig. 12 Sweeping Plane for Test 8

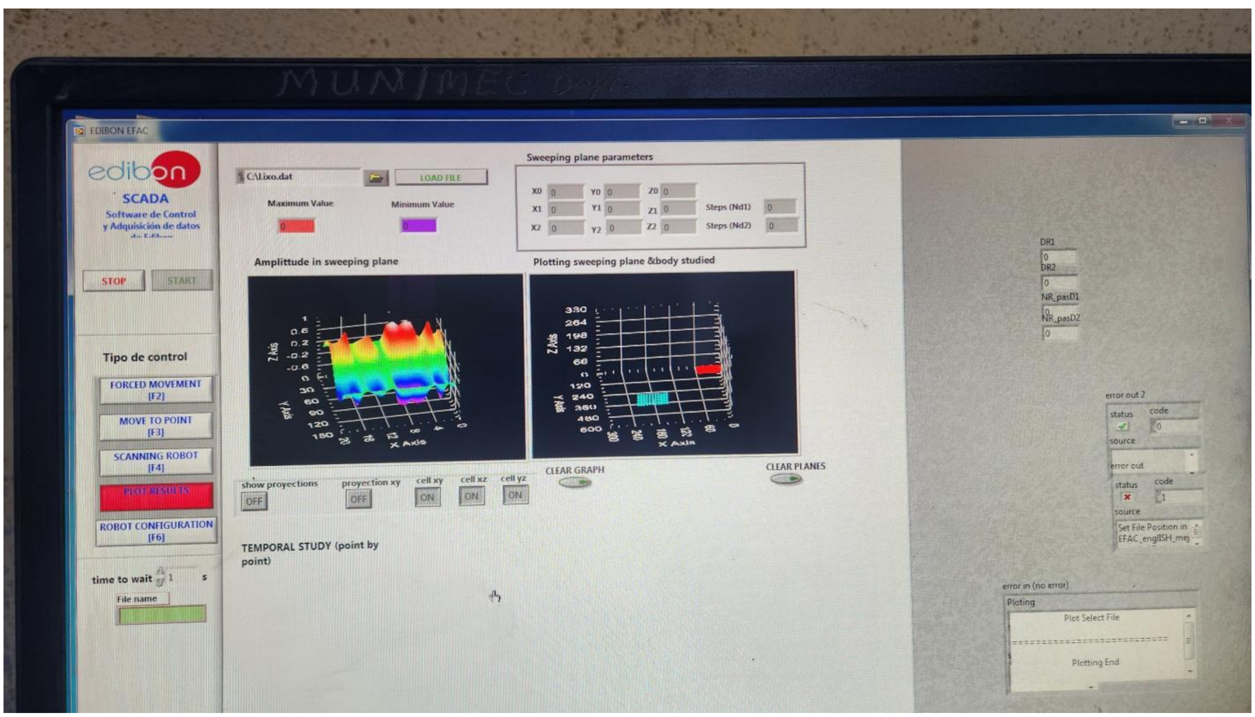

Fig. 13 Sweeping Plane for Test 9

4.2 Analysis of Results

Coordinates:

The x-coordinate remains constant at 273 mm

The y-coordinate remains constant at 250 mm

The z-coordinate remains constant at 168 mm.

This is because the distance between the hot and cold focuses was kept constant at 280mm and only the variation of the temperature distribution was taken into account.

Temperature:

The temperature of the hot focus in the barrel wall was increased by 5°C after every test carried out and the temperature of the cold focus was maintained at a certain range of temperature of between 3 and 10°C. The difference in temperature after the nine test carried out is small, implying a highly stable or uniform thermal environment over the measured distance. The minimal temperature variation suggests that the system fluid (water) is either well insulated, or is in a steady-state condition with negligible heat flow. The distribution showed a linear relationship between temperature and distance up to a peak position from the base, indicating temperature rise with distance.

5.0 Conclusion

Variation of temperature distribution in a convection heat transfer medium was undertaken.

Results show linear variation of temperature with distance up to a certain location. Results also show even distribution of heat (temperature) along the various coordinates.

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