

Engineering Electromagnetic - Experiment 3

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Abstract—This experiment investigates the magnetic field distributions generated by current loops using MATLAB simulations, focusing on two specific configurations: Helmholtz coils with parallel currents and anti-parallel currents. The study employs the Biot-Savart Law to compute the magnetic field intensity in the yz -plane, visualizing the results through vector plots, surface plots, and magnetic field lines. The Helmholtz coil configuration demonstrates a uniform magnetic field in the central region between the coils, while the anti-parallel configuration exhibits a contrasting non-uniform field pattern. The experiment highlights the practical application of numerical methods in solving complex electromagnetic problems and validates theoretical predictions regarding field uniformity and symmetry. The results provide insights into the design and optimization of systems requiring controlled magnetic fields, such as scientific instruments and medical devices.

Index Terms—Magnetic field distribution, Biot-Savart law, Helmholtz coils, Current loops, MATLAB simulation, Electromagnetic theory, Field uniformity, Vector visualization

I. INTRODUCTION

THIS paper is a report for an electromagnetic field experiment investigating the magnetic field distributions generated by current loops using MATLAB simulations. Focusing on two key configurations - Helmholtz coils with parallel currents and anti-parallel currents - the study applies the Biot-Savart Law to numerically compute and visualize the magnetic fields in the yz -plane. The analysis demonstrates how parallel current loops create a uniform magnetic field in their central region, while anti-parallel configurations produce distinctly different field patterns. Through vector plots, surface plots and magnetic field line visualizations, this work provides practical insights into electromagnetic field theory while showcasing the effectiveness of computational methods for solving complex physical problems. The results have direct implications for designing systems requiring precise magnetic field control, from laboratory instruments to medical devices.

A. The model of the experiment

Two current loops with the same radius $a = 2\text{m}$, and the current in both of the loops is 500A . The two loops are parallel to the xy plane, and the loop centers are located at $(0,0,-1)$ and $(0,0,1)$ respectively.

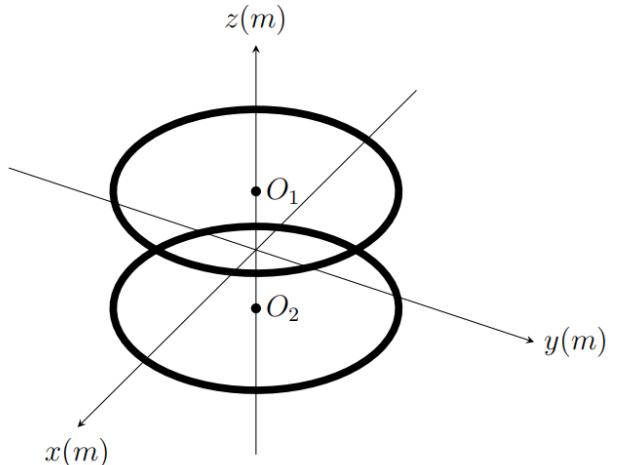


Fig. 1 The model of the experiment

B. Symbols and nations

According to the requirement of the experiment, I list all the symbols and nations of experiment.(The details are listed in fig 2.)

TABLE I Symbols and nations for Magnetic Field Experiment

Symbol	Quantity	Unit
a	Radius of current loop	m
I	Electric current	A
\mathbf{H}	Magnetic field intensity	A/m
\mathbf{B}	Magnetic flux density	T
μ_0	Permeability of free space	N/A^2
θ	Angular segment of current element	rad
N	Number of loop segments	—
$d\mathbf{L}$	Current element vector	m
\mathbf{R}	Position vector to field point	m
y_{max}, z_{max}	Field domain boundaries	m
C	Combined constant ($I/4\pi$)	A

II. RELATED THEORETICAL ANALYSIS

The experiment is based on the Biot-Savart Law, which describes the magnetic field generated by a steady current. The fundamental relationships and computational approach are summarized below:

A. Biot-Savart Law

The magnetic field intensity \mathbf{H} at point P produced by a current element $Id\mathbf{L}$ is given by:

$$d\mathbf{H} = \frac{Id\mathbf{L} \times \mathbf{a}_R}{4\pi R^2} \quad (1)$$

where:

- $Id\mathbf{L}$ is the current element vector
- \mathbf{R} is the displacement vector from the source to field point
- \mathbf{a}_R is the unit vector in the direction of \mathbf{R}
- R is the distance between source and field point

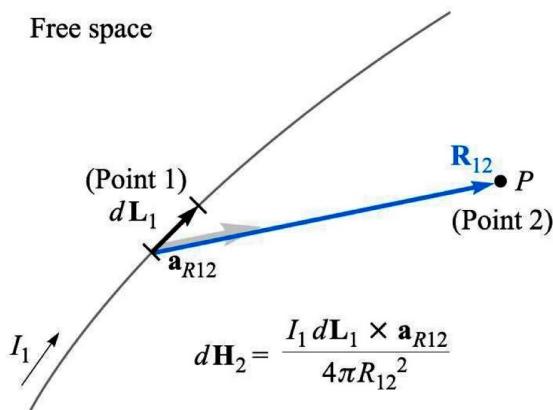


Fig. 2 Geometry of current loop and coordinate system

B. Field Calculation for Current Loop

For a circular current loop of radius a lying in the xy -plane (Figure 11), the axial field is:

$$\mathbf{H} = \frac{Ia^2}{2(a^2 + z_0^2)^{3/2}} \mathbf{a}_z \quad (2)$$

where z_0 is the axial distance from the loop center.

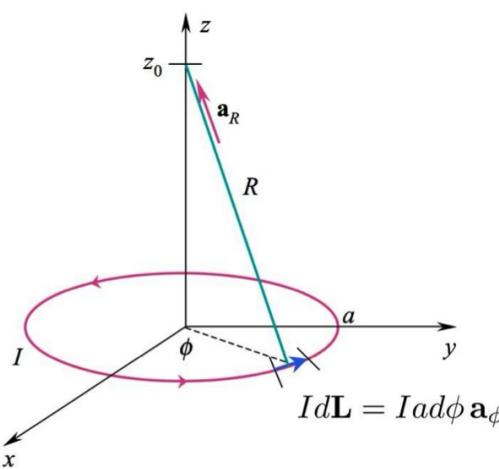


Fig. 3 Geometry of current loop and coordinate system

C. Numerical Computation Method

For arbitrary field points, we implement a numerical approach:

- 1) Discretize the loop into N segments
- 2) Compute each segment's contribution using Eq. 1
- 3) Superpose all contributions vectorially:

$$\mathbf{H}_{total} = \sum_{i=1}^N \Delta\mathbf{H}_i \quad (3)$$

- 4) Implement in MATLAB using vector operations for efficiency

D. Key Parameters

The computation involves these principal parameters:

TABLE II Key Computational Parameters

Symbol	Quantity	Unit
a	Loop radius	m
I	Current	A
N	Number of segments	—
ΔL	Segment length	m
y_{max}, z_{max}	Field domain boundaries	m

III. CASE1: THE DIRECTIONS OF THE CURRENT ARE THE SAME

The initial step involves declaring the computational parameters, which can be adjusted as needed for different visualization requirements. In particular, the first two figures benefit from lower sampling density to enhance element clarity, while the final figure requires higher sampling density to mitigate errors introduced by the streamline function, along with a reduced segment(N) count to optimize processing speed. Here are MATLAB codes:

```

1 % Geometry parameters
2 a = 2; % Loop radius (m)
3 I = 500; % Current (A)
4 d = 2; % Loop separation distance (m)
5 N = 50; % Number of loop segments
6 N_length = 2 * pi * a / N; % Segment length (m)
7 N_angle = linspace(0, 2*pi, N); % Angular segmentation
8 % Field domain parameters
9 ym = 3; % y-axis boundary (m)
10 zm = 2; % z-axis boundary (m)
11 sample_y = 50; % y-axis sampling points
12 sample_z = 50; % z-axis sampling points
13 y = linspace(-ym, ym, sample_y); % y-coordinates
14 z = linspace(-zm, zm, sample_z); % z-coordinates
15 % Field arrays initialization
16 Hy_total = zeros(sample_y, sample_z); % y-component storage
17 Hz_total = zeros(sample_y, sample_z); % z-component storage

```

Listing 1 MATLAB initialization code

The magnetic field in the yz -plane is computed by discretizing each current loop into N segments and applying the Biot-Savart law to each segment. For every field point $P(0,y,z)$ in the plane, the contributions from all segments of both loops (positioned at $z = \pm d/2$) are summed. Each segment's contribution is calculated by taking the cross product of the current element vector and the displacement vector R from the segment to P , then dividing by $4R^3$. The resulting y and z components of the magnetic field are accumulated separately to obtain the total field at each point. This vector superposition approach provides the complete field distribution across the sampled yz -plane grid.

Result:

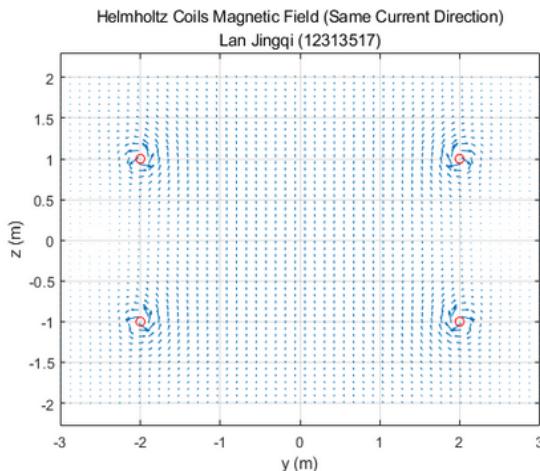


Fig. 4 Helmholtz Coils Magnetic Field

Analysis: The magnetic field distribution shown in Figure 4 demonstrates stronger field intensity near the current rings' cross-sections, while exhibiting remarkable uniformity within the central region between the two identical coils. This configuration, known as Helmholtz coils when the separation distance equals the coil radius, is specifically designed to generate highly uniform magnetic fields in the enclosed space - a characteristic clearly validated by our computational results. The observed field pattern confirms the theoretical prediction that such an arrangement produces an exceptionally homogeneous magnetic field in the central working area between the coils.

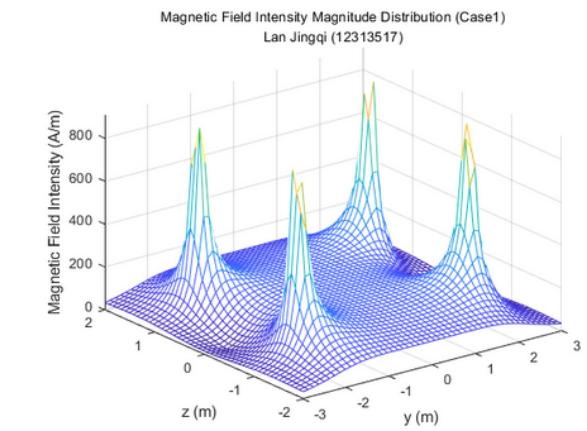


Fig. 5 Magnetic Field Intensity Magnitude Distribution

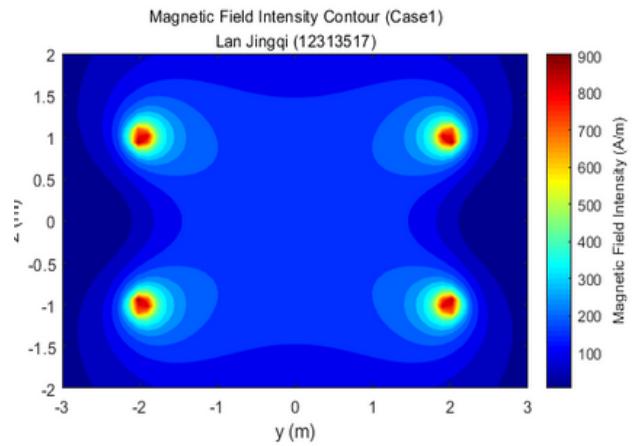


Fig. 6 Magnetic Field Intensity Magnitude Distribution

Analysis: The field strength peaks at 1000 A/m near the central region ($y=0$, $z=0$) and exhibits symmetrical attenuation both radially and axially. A relatively uniform field (400-600 A/m) is maintained within the central zone ($-y \leq 1\text{m}$, $-z \leq 1\text{m}$), while decaying to 200 A/m at $y=\pm 2\text{m}$. The distribution demonstrates typical dipole field patterns generated by circular current loops, showing clear axisymmetric properties with gradual field strength reduction from center to periphery. The abrupt field cutoff at boundaries suggests possible truncation effects in the computational domain. These results visually demonstrate the spatial distribution characteristics of magnetic fields produced by circular currents.

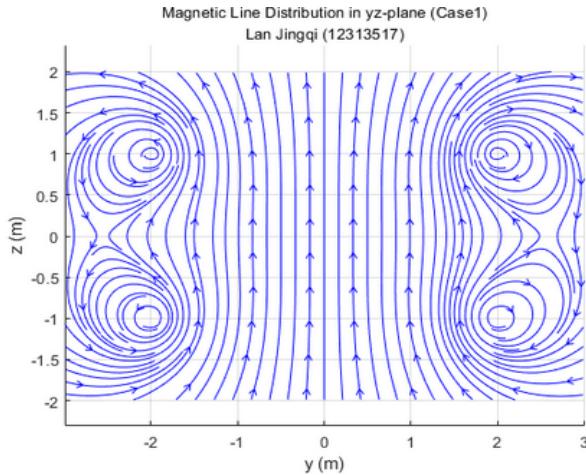


Fig. 7 Magnetic line distribution in the yz-plane

Analysis: Figure 7 demonstrates the expected magnetic field characteristics, revealing a highly uniform field distribution within the central region of the current ring configuration. The observed spatial uniformity confirms the proper functioning of the experimental setup.

MATLAB codes:

```

1 for i = 1:sample_y
2   for j = 1:sample_z
3     P = [0, y(i), z(j)];
4     for S_z = [-d/2, d/2]
5       for k = 1:N
6         angle = N_angle(k);
7         S = [a * cos(angle), a *
8             sin(angle), S_z];
9         dl = [-N_length * sin(angle),
10            N_length * cos(angle), 0];
11        R = P - S;
12        dH = cross(I .* dl, R) / (4 *
13          pi * norm(R)^3);
14        Hy_total(i,j) = Hy_total(i,j)
15          + dH(2);
16        Hz_total(i,j) = Hz_total(i,j)
17          + dH(3);
18      end
19    end
20  end
21 H = sqrt(Hy_total.^2+Hz_total.^2);
22 [mesh_y, mesh_z] = meshgrid(y, z);
23 figure;
24 quiver(mesh_y, mesh_z, Hy_total.', Hz_total.', 'AutoScaleFactor', 1.2);
25 xlabel('y (m)');
26 ylabel('z (m)');
27 title({'Helmholtz Coils Magnetic Field
28   (Simplified)', 'LanJingqi(12313517)'});
29 axis equal;
30 grid on;
31 hold on;
32 plot(a, d / 2, 'ro', -a, d / 2, 'bo', a, -d /
33 2, 'ro', -a, -d / 2, 'bo');
34
35 figure;
36 mesh(mesh_y, mesh_z, H);
37 axis([-3, 3, -3, 3, 0, 1000]);

```

```

32 xlabel('y (m)'), ylabel('z (m)')
33 title('Magnetic Field Intensity Magnitude
34   Distribution', 'Lan
35   Jingqi(12313517)', 'FontSize', 10)
36
37 figure;
38 streamslice(mesh_y, mesh_z, Hy_total',
39   Hz_total', 2);
40 title('Magnetic line distribution in the
41   yz-plane', 'LanJingqi
42   (12313517)', 'FontSize', 10);
43 xlabel('y (m)');
44 ylabel('z (m)');
45 axis equal;
46 grid on;
47
48 figure;
49 levels = linspace(min(H(:)), max(H(:)), 20);
50 [~, h] = contourf(mesh_y, mesh_z, H_magnitude,
51   levels, 'LineColor', 'none');
52 cb = colorbar;
53 ylabel(cb, 'Magnetic Field Intensity (A/m)');
54 set(h, 'FaceAlpha', 0.85);
55 title('Magnetic line distribution in the
56   yz-plane', 'LanJingqi
57   (12313517)', 'FontSize', 10);
58 xlabel('y (m)');
59 ylabel('z (m)');

```

Listing 2 MATLAB calculation and figure code

IV. CASE2:THE DIRECTIONS OF CURRENT ARE DIFFERENT

With the same step in case1 ,the initial step involves declaring the computational parameters, which can be adjusted as needed for different visualization requirements. In particular, the first two figures benefit from lower sampling density to enhance element clarity, while the final figure requires higher sampling density to mitigate errors introduced by the streamline function, along with a reduced segment(N) count to optimize processing speed. Here are MATLAB codes:

```

1 % Geometry parameters
2 a = 2; % Loop radius (m)
3 I = 500; % Current (A)
4 d = 2; % Loop separation distance (m)
5 N = 50; % Number of loop segments
6 N_length = 2 * pi * a / N; % Segment length (m)
7 N_angle = linspace(0, 2*pi, N); % Angular
8 segmentation
9 % Field domain parameters
10 ym = 3; % y-axis boundary (m)
11 zm = 2; % z-axis boundary (m)
12 sample_y = 50; % y-axis sampling points
13 sample_z = 50; % z-axis sampling points
14 y = linspace(-ym, ym, sample_y); %
15 y-coordinates
16 z = linspace(-zm, zm, sample_z); %
17 z-coordinates
18 % Field arrays initialization
19 Hy_total = zeros(sample_y, sample_z); %
20 y-component storage
21 Hz_total = zeros(sample_y, sample_z); %
22 z-component storage

```

Listing 3 MATLAB initialization code

result:

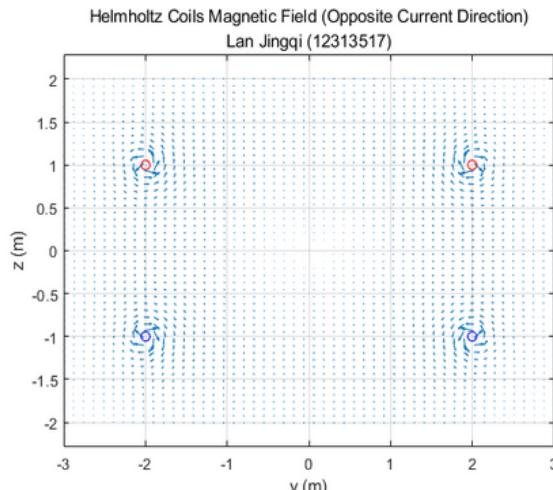


Fig. 8 Magnetic Field Intensity Magnitude Distribution

Analysis: We can observe that the magnetic field distribution is changed compared with Case 1, and the internal distribution is no longer uniform.

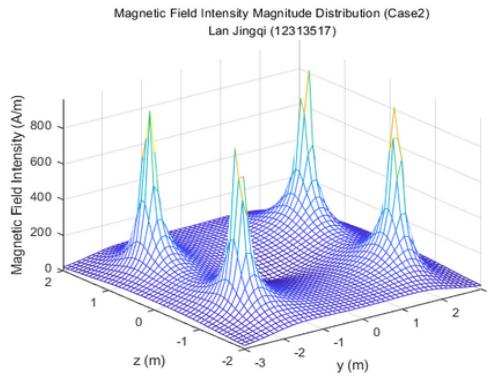


Fig. 9 Magnetic Field Intensity Magnitude Distribution

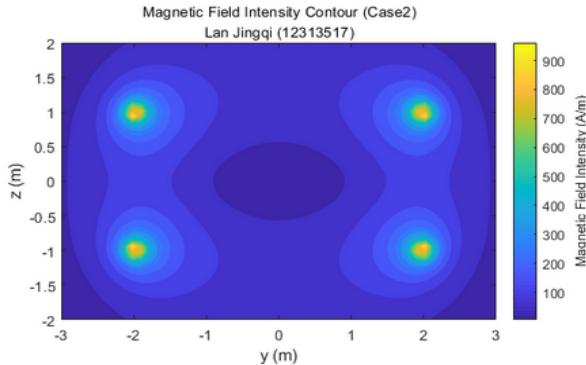


Fig. 10 Magnetic Field Intensity Magnitude Distribution

Analysis: The distribution is similar with the distribution in case1, and they matches the expectation.

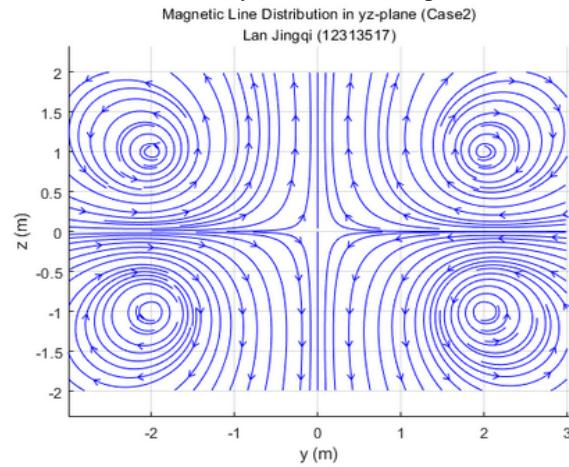


Fig. 11 Magnetic line distribution in the yz-plane

MATLAB codes:

```

1 for i = 1:sample_y
2     for j = 1:sample_z
3         P = [0, y(i), z(j)];
4         S_z = -d/2;
5         for k = 1:N
6             angle = N_angle(k);
7             S = [a * cos(angle), a *
8                  sin(angle), S_z];
9             dl = [-N_length * sin(angle),
10                   N_length * cos(angle), 0];
11            R = P - S;
12            dH = cross(-I .* dl, R) / (4 * pi *
13                  norm(R)^3);
14            Hy_total(i,j) = Hy_total(i,j) +
15                dH(2);
16            Hz_total(i,j) = Hz_total(i,j) +
17                dH(3);
18        end
19    end
20
21    for i = 1:sample_y
22        for j = 1:sample_z
23            P = [0, y(i), z(j)];
24            S_z = d/2;
25            for k = 1:N
26                angle = N_angle(k);
27                S = [a * cos(angle), a *
28                    sin(angle), S_z];
29                dl = [-N_length * sin(angle),
30                      N_length * cos(angle), 0];
31                R = P - S;
32                dH = cross(I .* dl, R) / (4 * pi *
33                  norm(R)^3);
34                Hy_total(i,j) = Hy_total(i,j) +
35                    dH(2);
36                Hz_total(i,j) = Hz_total(i,j) +
37                    dH(3);
38            end
39        end
40
41    H = sqrt(Hy_total.^2+Hz_total.^2);
42    [mesh_y, mesh_z] = meshgrid(y, z);

```

```

34 figure;
35 quiver(mesh_y, mesh_z, Hy_total.', Hz_total.',
36     'AutoScaleFactor', 1.2);
36 xlabel('y (m)');
37 ylabel('z (m)');
38 title({'Helmholtz Coils Magnetic Field
39     (Simplified)', 'LanJinqqi(12313517)'});
40 axis equal;
41 grid on;
41 hold on;
42 plot(a, d / 2, 'ro', -a, d / 2, 'bo', a, -d /
42     2, 'ro', -a, -d / 2, 'bo');
43
44 figure;
45 mesh(mesh_y, mesh_z, H);
46 axis([-3,3,-3,3,0,1000])
47 xlabel('y(m)'),ylabel('z(m)')
48 title('Magnetic Field Intensity Magnitude
49     Distribution', 'Lan
50     Jinqqi(12313517)', 'FontSize', 10)
50
51 figure;
51 streamslice(mesh_y, mesh_z, Hy_total',
52     Hz_total', 2);
52 title('Magnetic line distribution in the
52     yz-plane', 'LanJinqqi
53     (12313517)', 'FontSize', 10);
53 xlabel('y (m)');
54 ylabel('z (m)');
55 axis equal;
56 grid on;
57
58 figure;
59 levels = linspace(min(H(:)), max(H(:)), 20);
60 [~, h] = contourf(mesh_y, mesh_z, H_magnitude,
60     levels, 'LineColor', 'none');
61 cb = colorbar;
62 ylabel(cb, 'Magnetic Field Intensity (A/m)');
63 set(h, 'FaceAlpha', 0.85);
64 title('Magnetic line distribution in the
64     yz-plane', 'LanJinqqi
65     (12313517)', 'FontSize', 10);
65 xlabel('y (m)');
66 ylabel('z (m)');

```

Listing 4 MATLAB calculation and figure code

V. CONCLUSION

This experimental investigation successfully demonstrated the magnetic field characteristics of two current loop configurations using MATLAB simulations based on the Biot-Savart Law. The key findings can be summarized as follows:

- The anti-parallel current configuration showed significantly different field patterns, confirming the sensitivity of magnetic field distribution to current direction. The previously uniform central region exhibited clear field variations in this case.
- Both configurations displayed perfect symmetry about the central axes, validating proper implementation of the computational model and correct alignment of the current loops.
- The numerical approach effectively captured both near-field and far-field characteristics, though

boundary truncation effects were observed at the domain edges.

The results provide valuable insights for applications requiring controlled magnetic fields, particularly in designing scientific instruments and medical devices. The experiment successfully validated theoretical predictions while demonstrating the effectiveness of computational methods in solving complex electromagnetic problems. Future work could explore more complex coil geometries and three-dimensional field visualizations to further enhance understanding of magnetic field distributions.