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Improving Performance of Electromagnetic Induction Injera Mitad

Feleke Fanta

[1]*Lecturer, Electrical Power and Control Engineering, ADAMA Science and Technology University, Ethiopia*

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***Abstract: -** Injera is one of the basic food items for Ethiopian people. There are different devices used to cook injera in different parts of the country. Depending on the grain type, batter viscosity and other conditions, injera baking requires temperature ranging from 150°C to 180°C. In places where electrical energy is available, locally manufactured electric injera mitad is used. It has excessive heat loss and consequently low efficiency [1]. Aiming to solve these limitations, in March 2019 the author with his partner developed Electromagnetic induction Injera Mitad (EMIM) prototype [2]. Operation of the prototype was based on principle of electromagnetic induction. From the final test results it was observed that distribution of temperature along radial direction of the workpiece was not uniform. Uniform temperature distribution is one of the main factors which determine quality of Ethiopian injera. The difference between maximum and minimum recoded values was around 39°C. Thus, this work is proposed to improve the temperature distribution by using non-uniform spaces between coil turns. The coil was wound in the grooves with non-uniform inter-turn spaces. As a result, the temperature difference between maximum and minimum readings along radial direction was less than 15°C in which our objective was achieved. Also the initial heating up time was reduced to 6.5 - 7.5 minutes which improves power consumption and efficiency of the device.*

Key words: - working coil, cast iron, eddy current, inter-turn space, temperature, Injera Mitad.

Introduction

Injera is flat, thin, soft, bread like staple food item of most Ethiopians. Injera is cooked by a device or apparatus named mitad (plate) manufactured from special clay. By its very nature, injera has distinctive testing, texture with bubbly eyes at front face and smooth spongy surface at the back side. Injera can be produced from different staple grains such as teff, sorghum, millet, maize etc. Cooking injera with acceptable and good quality requires thorough understanding of the entire injera baking processes, such as fermenting under controlled environment, proper viscosity of batter, control of cooking temperature, excellent skill of the baker chef, etc.

In most Ethiopian households, injera baking is carried out using an open fire /three stone/ baking system in which the heat source is biomass (burning fuel wood, dung or agricultural residue).

In places where electricity is available, the locally manufactured electric injera mitad which uses resistive heaters as a heat source is used. The average power rating is around 3.5 KW[3]. Currently, there are around 1.3 million such traditional electric injera mitades in use [4]. The core problem of traditional Ethiopian electric injera mitad is its high energy consumption and low efficiency (45% - 55%) [1]. It consumes 60% to 70% of the total household energy demand.

Fig.1- Traditional 3 stone injera baking and injera, [5]

These limitations of locally manufactured electric injera mitad motivated the paper author and his partner to design and develop injera mitad prototype using electromagnetic induction principle.

Inductive heating is a contactless technique which converts electrical energy into heat based on the principle of electromagnetic induction. It uses the heating effect of ***eddy current*** and ***hysteresis* losses** in ferromagnetic materials. The basic principle of operation of induction heating is similar to the principle of operation of a transformer. The coil with its number of turns is taken as primary and the work piece (in our case the cast iron) as secondary. A high frequency current from resonant inverter is applied to the planar coil. The coil generates a high frequency magnetic field which couples the work piece and induces eddy current in it. The work piece (cast iron) is assumed to be homogeneous and is the source of heat.

In March 2019, the author with his partner developed electromagnetic induction injera mitad (EMIM) prototype. The major components of the developed electromagnetic induction injera mitad (EMIM) prototype were; resonant inverter to generate high frequency current, working coil to generate high frequency magnetic field, and cast iron workpiece to generate desired heat for injera baking.

Because of its peculiar magnetic and thermal characteristics, cast iron is used as the work piece to generate heat. Injera is baked directly on the cast iron whose surface is carefully seasoned to obtain nonstick surface. Thus, in the developed prototype the cast iron replaced both the heat source (resister) and clay mitad which are used in traditional electric injera mitad.

Based on literature and observations in the field, it was determined that the following characteristics define a good and acceptable quality of injera: clearly seen "Eyes" on top side, smooth underside, thin and crispy edges [4].

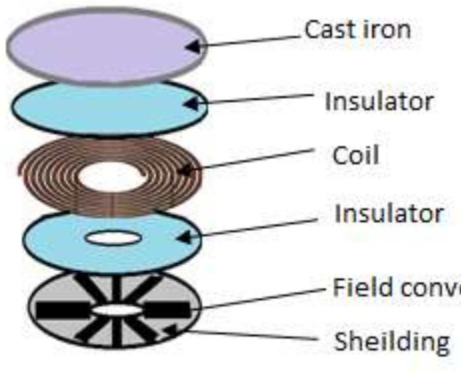


Fig. 2 - Structural arrangement of EMIM prototype

Parameters of working coil of EMIM prototype

A planar coil (one of the major components of EMIM) was wound and accommodated in uniformly partitioned grooves (throats) of ceramic insulator.

Table 1- Working coil parameters

No	Description	Symbol	value
1	Diameter of copper bundle	D_b	4 mm
2	Number of turns of the coil	N	32 turns
4	Outer diameter of the coil	D_{out}	440 mm
5	Inner diameter of the coil	D_{in}	30 mm
6	Inter-turn space (assumed uniform)	S	2.5 mm
7	Operating frequency	f	24 - 30 KHz

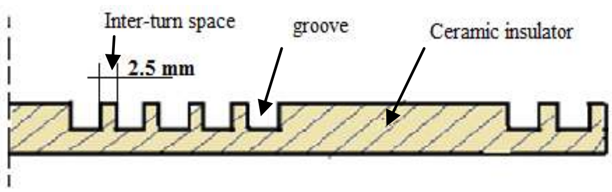


Fig. 3- Ceramic insulator with uniform inter turn space

The distribution of temperature in radial direction on the cast iron depends on the geometry of the cast iron and of the working coil, the electrical conductivity and magnetic permeability of the cast iron, and on the frequency of the working current which affects the skin thickness.

Table 2- Parameters of the cast iron.

No	Description	values
1	Density (Υ_w)	7150 kg/m^3
2	Relative permeability (μ_{rw})	250
3	Electrical Resistivity at room temperature (ρ_w)	9.61 x $10^{-8}\Omega$.m
4	Specific heat capacity (c_w)	460 J/Kg. ^oC
5	Thermal conductivity (λ_W)	50 W/m.K
6	Diameter (D_w)	450 mm
7	Thickness (h_w)	5 mm

The high frequency induced eddy current sheet in the cast iron (secondary) is the direct image of the working coil turns geometry (primary). As indicated in the fig 3, the coil turns are placed in uniformly partitioned ceramic grooves. To analyze the temperature distribution, a serious of laboratory and field test was conducted. Depending on the type of grain, viscosity of the batter, and other conditions, a quality injera is baked when the temperature of the cast iron is around 150^{o}C – 180^{o}C. The initial heating time to achieve this temperature on the prototype was around 8 – 9 minutes. The cast iron is heated from room temperature up to injera baking average temperature (175°C).

The following table shows initial heating up time and temperature development of cast iron up to the average temperature required to cook injera.

Table 3-Temperature distribution in cast iron with uniform inter-turn space

Time min	Cast iron radial length		
	0 – 51 mm	51 – 166 mm	166 – 225 mm
	T°C	T°C	T°C
0	23	23	23
1	52	58	41
2	62	87	56
3	79	98	70
4	95	116	83
5	111	133	95
6	125	143	109
7	136	154	125
8	149	169	131
9	158	179	140

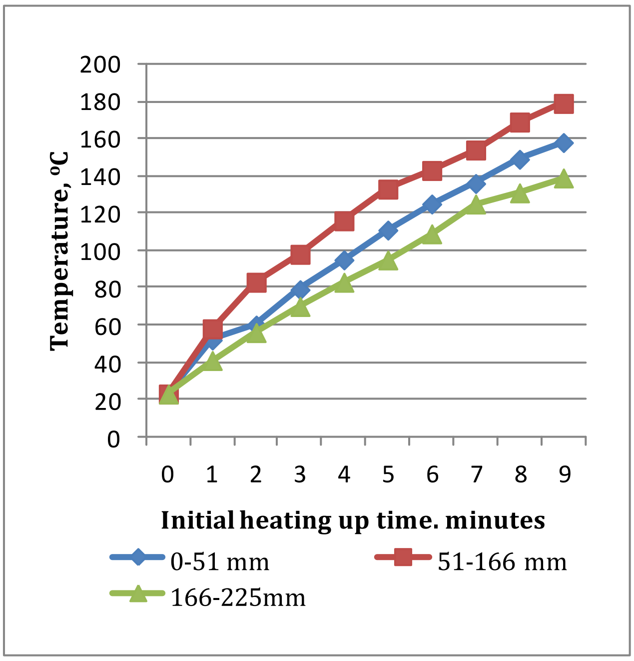
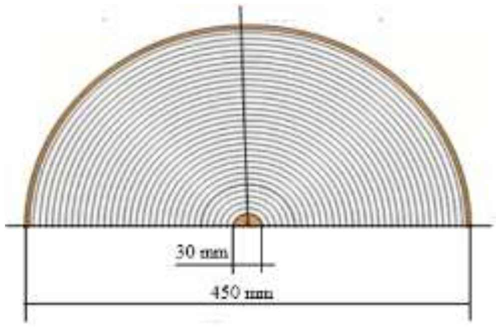


Fig.4-Temperature development during initial heating up time.

The following table shows recorded temperature of the prototype after initial heating up time was elapsed. It was highest at around the midpoint of the radius of the cast iron and decreases in both directions where it is around 158°C at the center and 140°C at the edge of the cast iron.

Table 4 Average temperature distribution along radial direction of the cast iron with uniform inter-turn space.

Radial length, mm	Tem. After 9 min. °C.
0	158
40	163
80	170
120	179
160	168
200	155
220	140



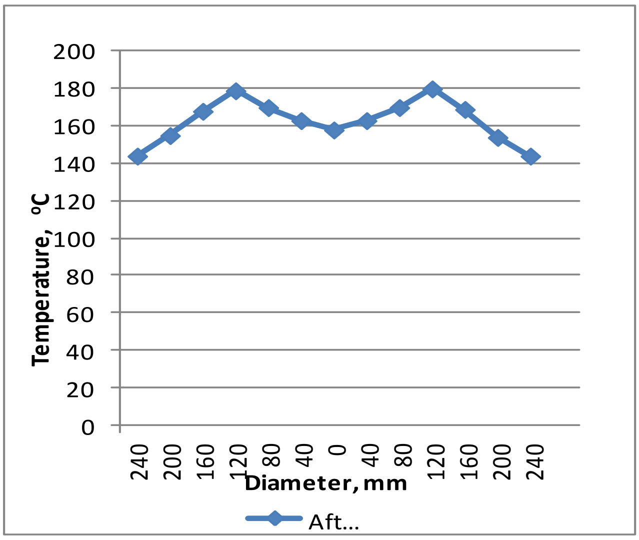


Fig. 5 - Temperature profile along radial direction of the cast iron disc

After the initial heating up time, the temperature of the prototype reached around 175°C in which the device is ready to cook injera. During testing the performance of the prototype, we obtained injera with a very good and acceptable quality as reported in the previous document [2]. However, as can be seen from the table 4 the temperature difference between maximum and minimum readings was around 39°C. If this temperature difference is improved, obviously we can get injera with much better improved quality. Thus, the main aim of this work is to optimize and improve the distribution of temperature along the radial direction of the cast iron. This could be achieved by maintaining non uniform inter turn space of the coil which results in uniform magnetic field distribution and thereby uniform distribution of induced eddy currents in the radial direction of the cast iron.

To optimize the distribution of temperature, the coil radial length is divided roughly in to the following three regions so that within each corresponding region of the cast iron the temperature difference is expected to be less than 15°C.

1st region = 15mm + 6 turns x 6 .0mm ≈ 51 mm

2nd region = 15 turns x 7 mm ≈ 105 mm

3rd region = 11 turns x 5.5 mm + 8.5 mm ≈ 69

Total radius = 225 mm

Parameters of EMIM coil after optimization

Ceramic insulator in which working coil is accommodated is manufactured with non-uniform inter turn spaces as indicated in the table below and fig. 7. Working coil with the same diameter, number of turns and length was wound on the restructured ceramic insulator and a series of laboratory test was conducted. Table 6 shows recorded data of temperature distribution along radial direction.

Table 5- Coil geometry with different inter-turn spacing

Description	Regions	Inter-turn spacing
Inter-turn space (not uniform)	(0–51mm)	2.0 mm
	(51–166 mm)	3.0 mm
	(166–225 mm)	1.5 mm
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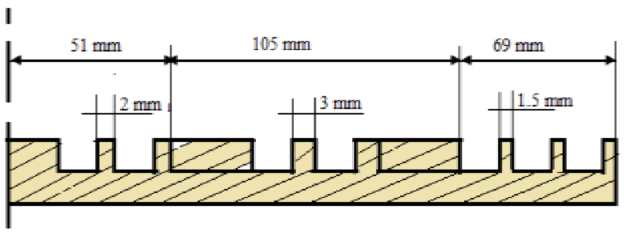
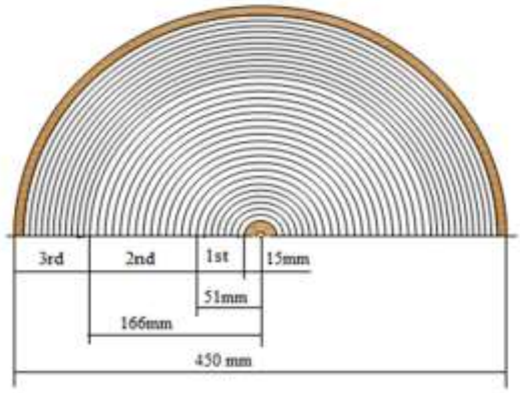


Fig. 7 - Ceramic with non- uniform inter-turn space

Table 6 - Average temperature distribution with non-uniform inter-turn space.

Radial length, mm	Temp. after 9 min. °C.
0	164
40	168
80	172
120	176
160	171
200	166
220	163



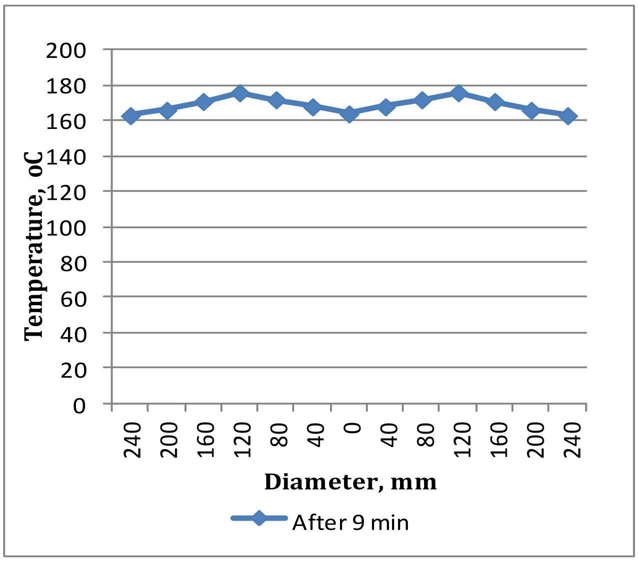


Fig.9 Eddy current and temperature profile along radial direction of the cast iron.

Results and Conclusion

As can be seen from the test results (table 8), with non-uniform inter-turn space arrangement of the coil, temperature distribution difference between the regions is less than 15°C which is the main objective of this work. This is due to the fact that induced eddy current magnitude along radial direction in the cast iron was improved compared to uniform inter-turn space arrangement. With this improved temperature distribution, the following achievements were obtained,

1. The temperature difference between maximum and minimum readings became 14°C (table 6) which was the objective of the work,

2. Initial heating up time was improved and reduced to 6.5 – 7.5 minutes to get injera baking temperature (175°C).
3. Due to this reduced pre heating time obviously efficiency of EMIM improved.
4, According to the professional local injera cooker (chef) and other observers, quality of injera cooked under this condition was much improved compared with previous case.

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BIOGRAPHY

Feleke Fanta M. received advanced diploma in electrical technology from Bahidar Polytechnic Institute, Ethiopia. Following graduation, he worked as electrician in Ethiopian Fabrics textile factory, Asmara.

He studied his BSc & MSc in Electromechanical Engineering at Zaparodje Machine Building Institute, Ukraine.
Following MSc graduation in 1990, he worked in different factories and government offices till 2004. Since September 2004, he has been lecturer in Adama Science and Technology in electrical power and control engineering department. His research interest includes Electrical machines and power electronics and electrical control system