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Computer-aided design of pancake coils for induction heaters

KAMALESH CHATTERJEE* AND V. RAMANARAYANAN
Department of Electrical Engineering, Indian Institute of Science, Bangalore 560 012, India.

Abstract

Pancake coils are used extensively in induction-heating applications. Closed-form design relationships for pancake coils are not available. Finite-element methods require powerful software. This paper gives a simple and quick numerical way of designing pancake coils. Calculated and measured results are presented. Measured results on asymmetrical coils are also presented. It is possible to relate empirically the predicted results of symmetrical coils to the measured results of asymmetrical coils

Key words: Magnetics, induction heater, induction coil.

1. Introduction

Induction heating is an energy-efficient method of heating. It can be applied profitably for domestic cooking. For heating flat-bottom vessels a pancake configuration of induction coil is well suited (Fig. 1).

It is not possible to obtain closed-form relations to design pancake coils. This paper applies the basic principles of magnetic fields to the case of pancake coils. The basic equations are solved numerically to obtain the inductance of air-cored pancake coils for different geometrical parameters (Fig. 2).

A number of pancake coils were built to verify the method of inductance prediction. The predicted results are presented along with the measured results for different geometrical parameters. The results are found to match within $\pm$ 7%.

A practical design of a pancake coil involves the calculation of wire size and the number of turns, for a given inductance value, current rating and inner diameter of the coil. The analysis may be modified to solve such design problems. An example of the same is illustrated.

With reference to Fig. 1, it may be seen that the field is used only on one side of the coil. The effective field strength may be increased by providing low-reluctance

* Present address: R and D Centre, Eureka Forbes Ltd, Bangalore 560 034.

return path at the bottom of the coil. With such asymmetrical coils, it will be necessary to resort to empirical relationships for the design. Measurements done on such asymmetrical coils suggest a suitable correction factor.

2. Pancake coil

A typical pancake coil is shown in Fig. 3. The current flowing in the coil is indicated in the usual convention. The geometrical parameters are as follows.

1) D_i = inner diameter of the coil
2) D_o = outer diameter of the coil
3) d_w = wire diameter
4) n = no. of turns.

3. Calculation technique

When the wire diameter is much less than the other geometrical dimensions of the coil (which will be true in most practical designs), it is a reasonable assumption to neglect wire diameter. Further, the magnetic effect of the spiral winding will be nearly the same as that of concentric rings carrying the same current. This simplification is illustrated in Fig. 4.

In order to evaluate the inductance of the coil, it is necessary to evaluate the self and mutual inductances of each of these current rings and add them all together.

3.1. *Inductance of a single-turn coil*

A single turn of coil and its magnetic field pattern is shown in Fig. 5. The inductance of the coil (or the flux linkage per unit current) is desired.

$$\text{inductance} = \frac{\text{flux linkage}}{\text{current}}.$$

In Fig. 5, consider a current-carrying ring of radius R. The flux distribution in the plane of the coil possesses circular symmetry. We may now define the following function.

$F(R,r)$ = The flux enclosed inside a circle of radius r on account of unit current flowing in the concentric current ring of radius R.

We may now see that $F(R,R)$ is the self inductance of the current ring of radius R. $F(R,R_1)$ is the mutual inductance of a turn of radius R_1 on account of a current ring at R. $F(R,r)$ may be evaluated from Ampere's law.

With reference to Fig. 6, flux density at point A due to current element dl is given by

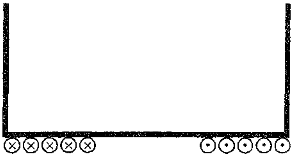

FIG 1 Pancake coil and flat-bottom vessel.

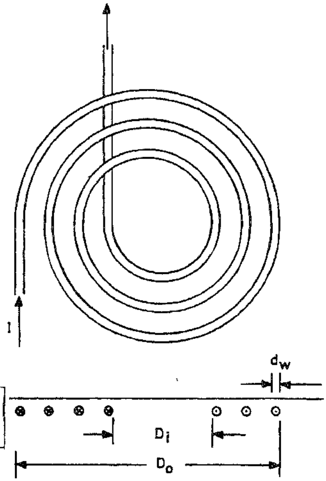

FIG. 3. A typical pancake coil.

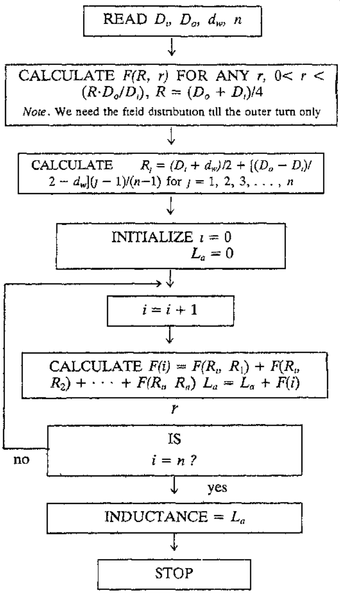

FIG. 2. Flow chart.

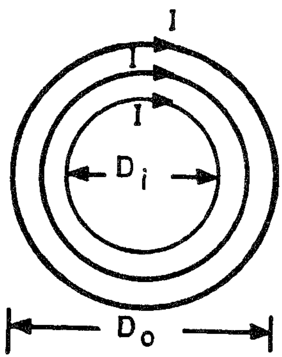

FIG. 4. Geometrical model of the coil.

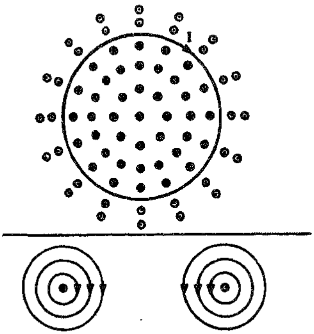

FIG. 5. Field pattern of a single-turn coil.

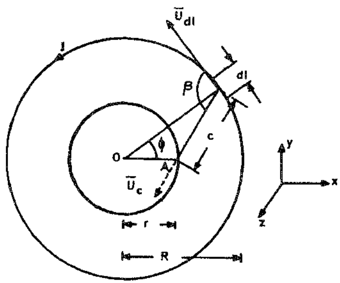

FIG 6. Flux density for a current element.

$$\overline{dB}(r,\phi) = \frac{\mu_0 \cdot I \cdot dl}{4 \cdot \pi \cdot c^2} \, \overline{U}_{dl} \times \overline{U}_c \tag{1}$$

where $\overline{U}_{dl}$ and $\overline{U}_c$ are the unit vectors in the direction shown in Fig. 6. The resultant field will be in negative z direction (out of the plane of paper). The magnitude of the field for unit current is given by

$$dB\ (r,\phi) = \frac{\mu_0 \cdot R \cdot d\phi \cdot \sin\ \beta}{4 \cdot \pi \cdot c^2} \ . \tag{2}$$

$\overline{dB}(r,\phi)$ integrated over 0 to 2π of ϕ will give the flux density $\overline{B}(r)$ at any radius r.

$$\overline{B}(r) = \int_{\phi\, =\, \cdot 0}^{\phi\, =\, 2\pi} \overline{dB}(r,\phi) \tag{3}$$

The flux density distribution as a function of r is shown in Fig. 7. It may be noticed that $\overline{B}(r)$ is not defined for $r = R$ (on account of our assumption that wire diameter is negligible). This is shown by a discontinuity in $\overline{B}(r)$ in Fig. 7.

$F(R,r)$ is evaluated by integrating $\overline{B}(r)$ over the appropriate area.

Case 1: For $r < R$, integration is straightforward.

$$F(R,r) = \int_{a\, =\, 0}^{a\, =\, r} \overline{B}(a) \cdot 2 \cdot \pi \cdot a \cdot da \ . \tag{4a}$$

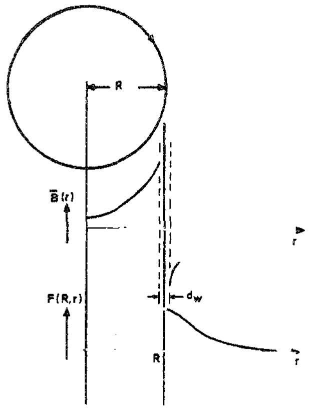

FIG. 7. $B(r)$ *vs* r and $F(R,r)$ *vs* r.

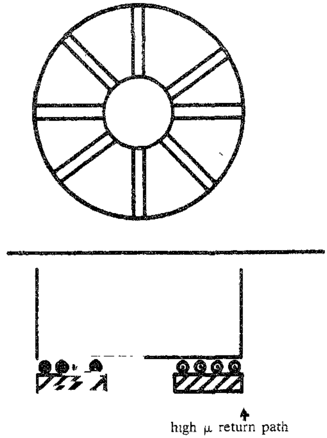

FIG. 8. Asymmetrical coil with vessel.

Case 2: For $r > R$, integration is done as follows

$$F(R,r) = \int_{a=0}^{a=R-d_w/2} \bar{B}(a)\cdot 2\cdot\pi\cdot a\cdot da + \int_{a=R+d_w/2}^{a=r} \bar{B}(a)\cdot 2\cdot\pi\cdot a\cdot da \ . \tag{4b}$$

This process will overcome problems in numerical evaluation without appreciably affecting the final result. The flux-enclosed $F(R,r)$ is shown in Fig. 7.

3.2. *Numerical evaluation of $F(R,r)$*

Integration of eqns (3), (4a) and (4b) is done by simple Euler's method. For the coils for which inductance is calculated, good accuracy is obtained for

$$\text{angular step size} = \nabla\phi < \pi/2000, \text{ and}$$
$$\text{radial step size} = \nabla R < R/2000.$$

But to save computing time without sacrificing accuracy ∇r and $\nabla\phi$ are selected according to the ratio r/R. Only near r/R close to 1 the above step size is taken but in other regions ∇r and $\nabla\phi$ are taken much larger.

3.3. *Relation between flux linkage and linear dimensions*

Consider two coils; one of radius R_1 and the other of radius R_2. It can be shown that

$$\frac{F(R_1,r_1)}{F(R_2,r_2)} = \frac{R_1}{R_2} \text{ if } r_2 = r_1 \frac{R_2}{R_1}. \tag{5}$$

If $F(R,r)$ is known for some R $[0 < r < \infty]$, using (5) we can get $F(R,r)$ for any R $[0 < r < \infty]$.

4. Calculation of inductance of a pancake coil

After having the curve of Fig. 7 and with eqn (5) calculation of coil inductance is simple. Each turn has been considered separately. For each turn its self and mutual inductance with all other turns are calculated and added together. Total inductance is the sum of all these results. The process is described with the help of a flow chart (Fig. 2).

5. Results

The calculated and measured results are presented in Table I. It can be seen that accuracy is good when wire diameter (d_w) is much less than the other geometrical parameters.

6. Design of symmetrical coils

Design specifications: L_a = coil inductance
I = rms current rating
J = allowable current density
D_i = inner diameter.

We are to calculate n and D_o.

Table I
Inductance of symmetrical pancake coils

Sl no	D_i *mm*	D_o *mm*	d_w *mm*	n	*Inductance in μH*		*error (%)*
					Calculated	*Measured*	
1	19	74·5	1·6	10	4·11	4·4	6·6
2	19	95	1·6	14	9·31	9·6	3·1
3	19	222·5	1·6	37	124·3	124·8	0·2
4	21	67	1·8	9	3·31	3·5	5·5
5	29	139	1·6	20	28·8	29·2	1·4
6	63·5	129	1·6	12	17·01	17·2	1·2
7	152	198	1·6	8	20·48	20·8	1·6
8	191	207	1·6	3	4·52	4·6	1·8

Step 1 : Determine d_w from rms current rating.

$$d_w = \sqrt{(4I/\pi J)}.$$

Select the wire. Determine d'_w = wire diameter with insulation.

Step 2: Start from the first turn. $n = 1$ and $D_o = (D_i + 2\ d'_w)$. Now D_i, D_o, d_w, n all four are known. Calculate the inductance as described in Section 4. If not matching with L_a, increase the number of turns such that,

$$D_o = D_i + (2 \cdot n \cdot d'_w)$$

and calculate the inductance, until it is nearest to L_a.

Step 3 : Note the value of n and D_o.

6.1. *Design example*

Required inductance = $60 \mu H$; *rms* current rating = 3 Amp; Allowable current density = $6 \times 10^6\ A/m^2$; D_i = 36 mm.

PVC-insulated copper wire 14/0·213 mm is selected. d_w becomes 1·1 mm. Wire diameter with insulation d'_w = 1·9 mm. The program gives the following results:

For, $n = 27$, inductance = 58·97 μH,
$n = 28$, inductance = 64·34 μH.

The coil has been built with 27 turns and the measured inductance is 60·3 μH.

7. Asymmetrical coils

In applications such as induction heating, the vessel is placed on top of the coil. Low-reluctance return path for the flux may be provided at the bottom of the coil to increase the working field intensity. For high-frequency applications, ferrite rods can be used for this purpose (Fig. 8).

Compared to symmetrical coils, such asymmetrical coils will provide more inductance for the same size. The factor by which the inductance increases should lie somewhere between one and two. This correction factor may be obtained from measurements made on representative coils. The coils are built such that

$$D_o - D_i = 2\ \text{(Ferrite rod length)}.$$

Geometrical configuration of placing 4, 8 and 16 rods is shown in Fig. 9. If the rods of appropriate length are placed symmetrically the correction factor becomes a strong function of the number of rods and a weak function of the other geometrical

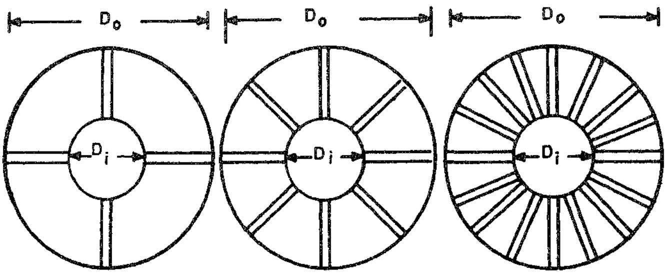

FIG. 9. Geometrical configuration of placing ferrite flat rods.

parameters. The reliability of the correction factor is verified for different coils with wide variation of geometrical parameters of which a few are given in Table II. Depending on the application one has to judiciously select the number of ferrite rods for the return path and the appropriate correction factor.

To design an asymmetrical pancake coil having inductance L with ferrite core, at first air-cored coil inductance is to be determined by dividing it by the correction factor. Design of air-cored coils is done as explained before.

8. Conclusion

The numerical evaluation of symmetrical pancake coils has been explained in detail. The accuracy of prediction is verified through measurements on several coils. The accuracy is found to be good, when the wire diameter is much less than the other

Table II
Correction factors for asymmetrical coils

D_i *mm*	D_o *mm*	d_w *mm*	n	*Inductance of air-cored coil in* μH	*Correction factor*		
					with 4 rods	*with 8 rods*	*with 16 rods*
29	139	1·6	20	29·2	1·29	1·44	1·59
31	140	1·0	28	61·2	1·30	1·46	1·62
29	140	0·8	33	82·2	1·32	1·47	1·61
19	182	1·0	43	144·7	1·33	1·47	1·62
19	65	1·0	12	5.71	1·29	1.45	1.58
100	207	1·0	28	149·8	1.32	1·46	1·63

linear dimensions of the coil. The above method can be used for the starting design of pancake coils. The proposed correction factors for asymmetrical coils will enable design of such practical pancake coils.

Reference

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