

Optimal Design of Internal Induction Coils

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ABSTRACT

Internal induction heating coils are not so well studied as external. Three main induction coil styles were proposed in pioneering works many years ago: Cylindrical coils, Hair-pin coils and Rod-type coils [1, 2]. It was clear from the very beginning that electromagnetic parameters of the coils of two first styles might be strongly improved by application of magnetic cores. However it was not clearly shown what parameters may be improved and how much, as well as what are the optimal designs of induction coils.

Current presentation contains short consideration and comparison of all three styles of coils followed by a detailed analysis of cylindrical internal (ID) coils using modern computer simulation tools. It is shown that it isn't sufficient to only consider the influence of magnetic core on electrical efficiency of the coil head. The cores reduce dramatically current demand for transfer of required power into the workpiece. In turn it results in strong reduction of voltage drop and power losses in the whole supplying circuitry: coil leads, busswork and matching transformer. Plus much smaller capacitor battery is required.

Computer simulation is simple for single-turn cylindrical ID coils and several computer packages may be used. Computer simulation of multi-turn cylindrical ID coils, which are the most common, is a much more complicated task, due to the return leg. The return leg makes the problem 3-D and special methods are required for simulating this case. The authors used a two-dimensional coupled program Flux2D and a program Elta based on a combination of 1D Finite-Difference method and special analytical procedures.

INTRODUCTION

Induction heating of internal (ID) surfaces is more complicated than heating of external surfaces because of a limited space available for induction coil and for magnetic flux return (magnetic flux back path). There are three main types of inductors for ID heating: central rod, hair-pin and cylindrical.

Inductor with a central rod

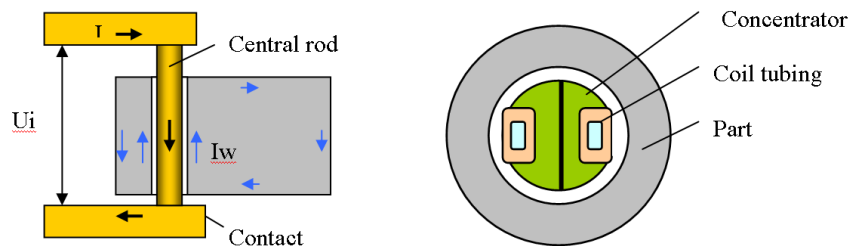


Figure 1. Central rod inductor (left) and hair-pin ID inductor (right)

This type of inductor is used not often because of a presence of electrical contact in its circuit. Inductor has a water-cooled rod, which goes through the bore in the work piece. Electric current is supplied to the ends of this rod. No concentrator is required with this

inductor. Eddy current induced on the ID surface of the work piece flows along the bore and returns back on the external surface preferably on the side of a busswork connecting the inductor to a heat station. Despite of electrical contact these coils work well with proper maintenance. Minimal bore diameter may be as small as 7 mm. Rotation of the part is desirable but not mandatory. The limitation of these inductors is that the whole internal surface must be heated and there is no real possibility to control the heat pattern in length.

Hair-pin ID coil

Relatively long ID surfaces may be heated by hair-pin ID coil. These coils must have concentrator preferably from MagnetoDielectric Material (MDM). It is recommended to make an insulation gap between two parts of concentrator. This gap prevents electrical break of concentrator from one conductor to another through the concentrator, resulting in coil short-circuiting. Part rotation is mandatory for this type of induction heating. Hair-pin coils may be successfully used for parts with variation of diameter or wall thickness in length. Coil conductor cross-section may be varied in length in order to provide required power distribution in the part. The other way is variation of concentrator dimensions in the coil length. Hair-pin coils may be used for heating of ID surfaces with diameter above 13 mm.

Single-turn cylindrical coils

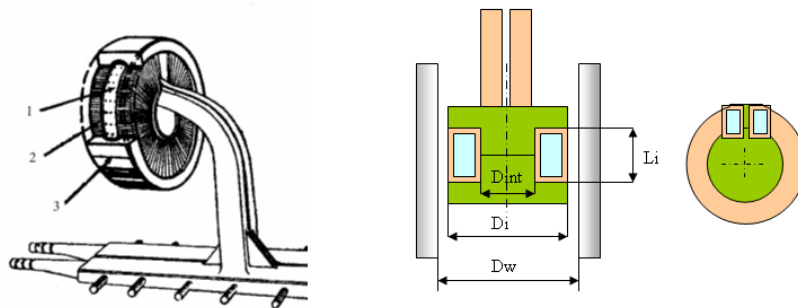


Figure 2. Single-turn ID coil with laminated core [1] (left), modern coil with MDM concentrator (center) and top view of the coil with removed top part of the concentrator (right). Left picture 1- coil tubing, 2-thin laminations, 3-bearing ring

Similar to OD coils, internal inductors may be single- or multi-turn. Single-turn coils are simple in design and may be successfully used for static heating of relatively short areas of ID surface ($L_i < 20-30$ mm) or for scanning heat treatment. For longer parts the coil current will be too high, resulting in big losses in the coil leads and in the busswork. Minimum diameter of the work piece D_w may be estimated on the following basis:

- Minimal internal diameter D_{int} of the coil may be assumed as 8 mm
- Minimum tube wall is 0.5 mm
- Radial dimension of cooling channel is 3 mm

It gives us an outer coil diameter $D_i = 17$ mm. With coupling gap between the part and coil equal to 1 mm, minimum internal workpiece diameter is 19 mm. For small and medium part diameter ($D_w < 100$ mm), magnetic flux concentrator is strongly desirable, while for larger coils it is also beneficial. Concentrator facilitates magnetic flux flow inside the coil and as a result improves coil efficiency and dramatically reduces current demand. For a given power transferred into the part, the coil head voltage remains approximately the same with and without concentrator. Lower current means lower losses in coil leads, busswork and matching transformer. In addition required capacitor battery may be several times smaller when the concentrator is installed.

Multi-turn cylindrical coils

For simultaneous heating of relatively long ID surfaces, multi-turn cylindrical coils may be used. Their design is similar to that of a single-turn coil but additional space is required to pull out the return lead (leg), Figure 3.

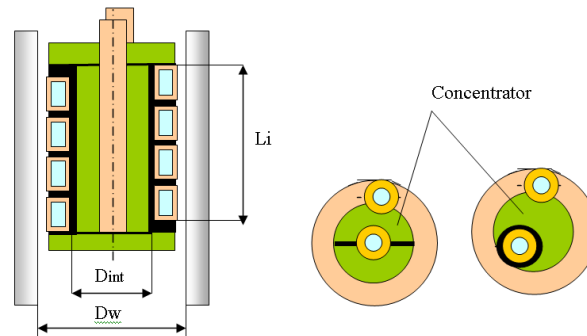


Figure 3. Multi-turn internal inductor: cross-section (left) and top view with two possible positions of the return leg

Design of internal multi-turn coil is shown in Figure 3. Concentrators may have additional discs on the top and bottom, which form the poles. These poles provide more precise heat pattern and improve the coil parameters. Minimal work piece diameter for heating with multi-turn coil may be calculated similar to a case with a single-turn coil. If return leg is 5 mm in diameter, concentrator and insulation thickness is 4 mm and coil tubing radial dimension is 4 mm, minimal workpiece diameter is around 23 mm. Two positions of return leg may be used – central and side, close to the winding (figure 3, right).

Electromagnetic field inside the multi-turn coil is essentially three-dimensional even in the case of central position of return leg, when the geometry is axisymmetrical. It is because there are two components of magnetic field in this area. Main field is generated by turns of the coil head. The lines of this two dimensional field are located in Z-R planes. The second field is one-dimensional. It is generated by return leg and its lines form circles around the return legs.

OPTIMAL DESIGN OF CYLINDRICAL COILS

Before discussing optimal design of internal inductors, it is necessary to show the specific features of ID coils compared to OD ones using a simplified equivalent magnetic circuit (Figure 4). This circuit shows that ampere-turns (IN) of the coil generate magnetic flux Φ and drive it around the turns of the induction coil. Values of Z_m and R_m represent corresponding magnetic resistances (reluctances) of the “active zone” (workpiece and coupling gap under the coil face) and of the return path inside the coil.

Compared to O.D. Induction Coils, I.D. Induction Coils have much higher values of R_m relative to Z_m . This is due to the small space available for flux to flow inside of the inductor. As a result, more ampere-turns (IN) are required to generate the magnetic flux (Φ) required to heat the workpiece.

This is also the reason why induction coils with a small coupling gap are more efficient than loosely coupled ones. Ideally, with a coupling gap close to zero, all of the magnetic flux in the “active zone” would flow through the workpiece surface generating eddy currents. In the real world though, the coupling gap is a bypass for magnetic flux in the “active zone”. The smaller the gap between the coil face and the workpiece, the smaller the total magnetic flux and less ampere turns required for its generation. Higher frequency is also beneficial for ID coils, especially for small coils with no magnetic concentrator (core).

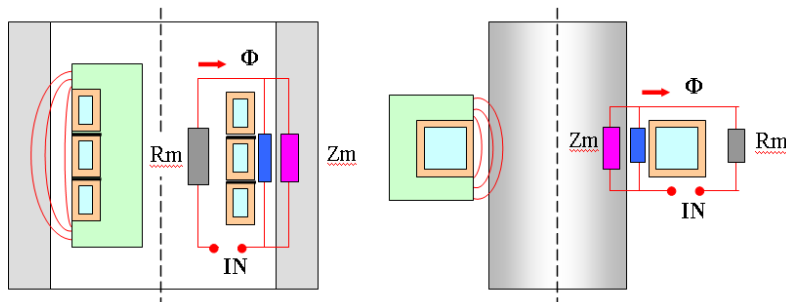


Figure 4. Equivalent magnetic circuits for I.D. (left) and O.D. (right) induction coils

For small I.D. coils without a magnetic flux controller, the value of **Rm** is often significantly larger than **Zm**. In these cases, nearly all of the ampere turns are used for driving the flux around the back path and very few are used for heating the workpiece. The power factor, efficiency and coil impedance of these coils are typically very bad.

If a good magnetic flux controller is applied as shown in the left hand side of figure 4, then the value of **Rm** will typically drop several times. This means that the ampere-turns of the coil will also decrease dramatically, leading to very strong improvement in the induction coil parameters.

For larger I.D. induction coils, there is more space for the magnetic flux to return through the center of the induction coil, therefore the value of **Rm** does not usually overwhelm the value of **Zm**, but it is often around the same size. Therefore, there is the possibility for the magnetic flux controller to provide sizeable benefits even for large I.D. inductors [4].

The next step is to move from qualitative results into quantitative ones. It is clear from the above considerations that one of the main factors in I.D. coil performance is the choice of magnetic flux controller. In multi-turn cylindrical coils, there are three options for the magnetic core:

1. No magnetic core at all
2. Magnetic core consisting of yoke only
3. Magnetic core consisting of yoke and poles

The reluctance, **Rm**, of the back path for the ID coil is close to the reluctance of the coil without the workpiece [3]. For the coil without a core, $R_m = N / (L_o K)$, where N is the coil turn number, L_o is the inductance of the coil without taking into account end effects and K is the Nagaoka coefficient. For this reason, analogs of Nagaoka coefficients for three cases were calculated for the coils with and without magnetic cores (Figure 5). It is clear that as the ratio D/l , where D is the coil diameter and l is the coil length, increases, the influence of the magnetic core on the Nagaoka coefficient decreases. However, the coefficient for the coils with magnetic core still remains much higher than for the coil without the core. Also, what is clear is that the presence of poles can dramatically improve the coil performance. The magnetic flux and therefore the coil voltage should be approximately the same to reach the same maximum temperature in a workpiece in a specified time. Thus, the higher the inductance, the lower the current demand. Lower current demand will lead to higher power factor, reduced losses in busswork and power supplying circuitry and a smaller capacitor battery. The results of this study are applicable to both single and multi-turn cylindrical internal heating coils.

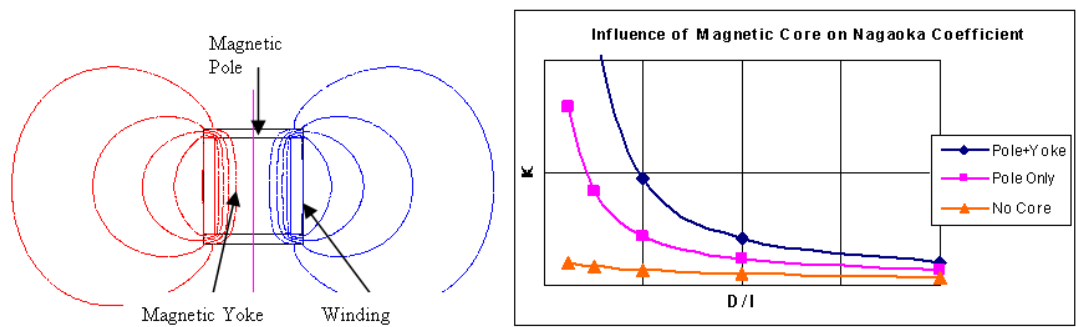


Figure 5. Basic geometry used for calculation of Nagaoka coefficients and resulting curves

The next step in studying the influence of a magnetic flux controller on internal heating coils is to look at an actual heating application. Let us consider the case of a stainless steel sleeve, which must be heated to 600 C in the center. This is representative of a brazing application or some type of surface modification process. The workpiece chosen has an ID of 5.6 cm, OD of 6.9 cm and length of 5.6 cm. The induction coil consists of four turns of 0.64 cm square copper tubing. The ID of the coil is 3.6 cm, OD is 4.8 cm and the overall length is 3 cm. The concentrator (if used) is Fluxtrol 50 with thickness 0.64 cm. The frequency used for simulation was 10 kHz and computer simulation program was Flux 2D. Axial current in the return leg is assumed to be zero. This geometry is shown in figure 6.

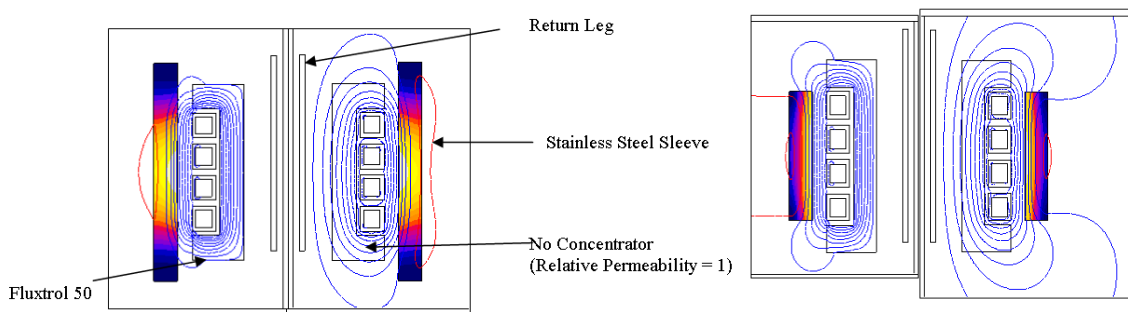


Figure 6. Internal induction heating of stainless steel sleeves with and without a magnetic flux controller. Left – sleeve length = 5.9 cm, Right – sleeve length = 3.0 cm

Figure 6 clearly shows that the path of the magnetic flux is strongly affected by the influence of the magnetic flux controller. This leads to not only a redistribution of current in the conductor, but also a concentration of the power density in length. The important results of this case are summarized in table 1.

Part length	Core	Pole	U	I	ΔP_c	P_{steel}	P_{total}	η	$\cos\phi$	S
55.9 mm	y	y	33.6	900	1685	8837	10522	84.0%	0.348	30240
55.9 mm	y	n	32.3	1190	2512	8878	11390	77.9%	0.296	38437
55.9 mm	n	n	32.9	2000	4168	9285	13453	69.0%	0.204	65800
30 mm	y	y	30.9	790	1242	8126	9368	86.7%	0.384	24411
30 mm	n	n	30.2	1760	3179	8282	11461	72.3%	0.216	53152

Table 1. Results of internal heating of stainless steel sleeves

As could be expected, the voltage required for the two cases is close to the same (33.6 V vs. 32.9 V). The electrical efficiency of the coil is significantly higher for the coil with Fluxtrol 50 core than for the one with air (84% compared to 69%). However, the current and reactive power required to achieve the temperature 600 C is more than 2 times higher for the bare coil than the one with Fluxtrol 50. This will lead to over 4 times the losses in the

busswork and current carrying conductors in the tank circuitry. It is important to mention that the copper losses in the coil head are 2.5 times higher for the bare coil instead of the 5 times from the rule of I^2 . It happens, because on the bare coil the current is flowing on both the OD and ID surfaces. Only considering the active area of the copper head, 28% more power is required to heat the center of the stainless steel sleeve to the same temperature. Taking into account the supplying circuitry, the real savings will be significantly higher.

The next case to consider is the heating of the entire internal length of a workpiece, for instance single shot hardening or a surface coating application. For better comparison, everything is the same as in the previous study except the length of the sleeve is reduced to 3 cm (the same length as the inductor). The geometry is shown in figure 6.

For the short sleeve, the temperature distributions are quite different from the case of the long sleeve. In this case, the temperature distributions with and without a magnetic flux controller are quite similar. This is due to the positive electromagnetic end effects of a non-magnetic workpiece and reduced soaking in the length of the sleeve. The electrical parameters are contained in Table 1.

The results clearly show that despite of similar temperature distributions, the electrical parameters are quite different. Once again, the voltage required with and without a magnetic flux controller is similar (30.9 compared to 30.2) and it is around 10% lower than in the case of the long sleeve. For both cases, current also declines just over 10% compared to the case of the longer workpiece. Efficiency is slightly higher for both cases and total power required is less due to reduced soaking in the length of the part.

As was discussed above, the magnetic field in real ID coils, especially multi-turn ones, is inherently 3-D in nature due to the orthogonal magnetic field sources (active turns and return leg). Optimization of these coils using direct 3-D coupled electromagnetic and thermal computer simulation would be a very time consuming and laborious procedure. To reduce the time and complexity of study, the authors utilized two programs, Flux 2D and ELTA, for simulation of these types of systems.

The newest version of program ELTA allows the user to simulate the whole system, including coil head, return leg, external busswork and even components of power supplying circuitry – matching transformer and capacitor battery. This program is based on combination of numerical and analytical methods. Analytical methods treat accurately circular and axial fields inside the coil, with and without concentrator. Numerical Finite-Difference Method is used for calculation of electromagnetic and thermal processes inside the part and coupling gap, accurately simulating the heating dynamics. To take into account the areas near the coil ends, where main magnetic flux is bending before entering inside the coil, additional analytical methods have been developed. These methods are based on calculation of magnetic resistance (reluctance) of end areas. Coefficients required for this calculation had been found using Flux 2D and experiments. ELTA is accurate enough for calculation of heating dynamics and system parameters.

For the above cases, where the ratio of D/l is relatively large, Flux 2D can be used for accurate simulation, because the influence of the return leg is relatively small. For small ID coils, this is not the case and ELTA must be used. As an example, consider the case of a 6 cm long, 6 turn coil for heating a sleeve with ID 3 cm and wall thickness 0.9 cm. Material is 1040 steel and the application is surface hardening to a depth of 0.1 cm. Oval tubing with dimensions 0.6 X 0.7 cm with return leg made of .64 cm round tubing. The inductor has two sections of leads, one of the same tubing as the return leg and the other one is in the form of busswork. The coil is connected to a 3:1 matching transformer and the core is made of Fluxtrol 50. Heating time is 8 seconds and the frequency is 80 kHz.

The average values of the coil parameters for the heating cycle are presented in Table 2. The magnetic core reduces the current demand 2.4 times in this application. The coil head voltage is the same for all three cases (85 V). It means that the voltage drop on the return legs is 47, 135 and 53 V respectively. That means that installing a 1 mm gap between the

core halves leads to an 82 V reduction in voltage drop on the return leg, which is almost the same as the coil head voltage! Insertion of the gap is essential for ID coil optimization.

Case	Core	Core Gap (mm)	Uind (V)	Iind (A)	Pind (kW)	η	cos ϕ	Sind (kVA)	Ugen (V)
1	No	NA	132	1350	34	55%	0.19	178	480
2	Yes	0	220	568	25.4	77%	0.22	125	760
3	Yes	1	138	570	25.4	77%	0.36	78	460

Table 2. Electrical parameters for ID hardening application

The performance and reliability of ID coils strongly depends upon the loading. In the above case, the magnitude of the magnetic flux density in the core material reaches 0.85T, which is very high for this frequency (80 kHz). For this reason, there is no resource for further power increase. For the bare coil, this limit will be reached even earlier due to copper coil losses from carrying too high currents.

It is clear from the above results that a magnetic flux controller is essential for optimal design of internal induction heating coils. So selecting the proper magnetic material for the core is an important step in the design phase. At the dawn of induction technology only laminations were available. Very thin laminations (0.05 – 0.07 mm, sometimes 0.03 mm) have been used for the core at middle and even radio frequency RF [1, 2]. Such concentrators are laborious in manufacturing and at RF must be intensively cooled by water.

At present time three types of magnetic materials are available for concentrators – laminations, ferrites and magnetodielectric materials. Application of ferrites is limited because they are brittle, non-machinable and have low saturation flux density. MDM's allow the designer to make any dimensions and shape of the core. An optimal design of concentrator is shown in Figure 1. The concentrator is made of magnetodielectric material such as Fluxtrol A or Fluxtrol 50. These materials are easily machinable and the concentrator may be made of two parts, which may be easily inserted into the coil from the top and bottom. It is recommended to glue the concentrator to the inductor turns using thermally conductive glue such as silica-filled epoxy compound.

CONCLUSIONS

Internal induction heating coils are more complicated than external ones are. There are three main styles of internal induction coils: hairpin, rod and cylindrical. Each type of internal induction coil has advantages and limitations in their application.

Analysis of cylindrical induction heating coils based upon computer simulation is presented. Computer simulation packages ELTA and Flux 2D were used for study; Flux 2D for coil head calculations and ELTA for simulation of the whole system including return leg, busswork and matching transformer.

It is shown that a magnetic flux controller (core) improves coil efficiency and drastically reduces current demand. Concentrator poles further improve coil performance and are recommended for optimal coil design.

It is shown that the voltage drop on the return leg may be very large when a tubular magnetic core is used. It is recommended to make the core of 2 half shells with a 1-2 mm spacer between them. This gap reduces core saturation by the circular field and strongly reduces the voltage drop on the return leg.

Further coil optimization is possible by shifting the return leg to one side of the inductor instead of centrally locating it. In this case, the return leg does not generate significant additional magnetic field and the core can be made of one piece.

New magnetodielectric materials (MDM's), such as Fluxtrol 50, are well suited for use as magnetic cores in ID coils due to excellent machinability, low magnetic losses, high saturation flux density and good permeability.

More research must be done to define the specific limitations of ID coil application in particular technologies.

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