Improved nanocrystalline core welding transformer with forced cooling

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Abstract **This paper discusses a method for dimensioning power nanocrystalline welding transformer with forced cooling.**

The design results and experimented transformers show the improvements when using a nanocrystalline core instead of classical ferrite cores (50% in volume and 4% in total weight of the component). Using forced cooling provides improvement of 23% in volume and 34% in total weight.

Keywords – **Soft Magnetic Materials, Nanocrystalline, Ferrites, Forced cooling.**

I. INTRODUCTION

Power electronic magnetic components suffer from core losses. The approaches to deal are better cores or better cooling – forced cooling. The new nanocrystalline alloys prove to be a first-rate material for power electronics [1,2], combined with low magnetic losses, the great permeability (20 000 to 600 000 vs. 10 000 for ferrites) and high saturation induction (1.2T vs. 0.4T for ferrites). Using forced cooling, the full benefit of the high induction of nanocrystalline material can be used.

II. HEAT TRANSFER MECHANISMS

There are three heat transfer mechanisms: conduction, convection and radiation.

A. Conduction heat transfer

Conduction heat transfer presents the energy transfer from a high temperature region to a low temperature region of a body in which there is a temperature gradient. The *heat transfer rate q* is proportional to the cross-sectional area *A* through which heat is being conducted and to the temperature gradient in the direction of the heat flow $\frac{\partial T}{\partial x}$ (direction normal to *A*):

A positive constant *k*, called *thermal conductivity*, is introduced:

$$q = -k\,A\frac{\partial T}{\partial x} \qquad (1)$$

where: q is the heat transfer rate, [W];

k is the conductivity of the material, [W/m^2 ·°C];

A is the cross-sectional area through which heat is being conducted, [m^2].

B. Convection Heat Transfer

Convection heat transfer is a complex process, involving conduction to the boundary level convecting fluid. The physical mechanism of convection is related to the heat conduction through a thin boundary layer of fluid, adjacent to the heated body surface. The heat transfer rate is determined by the velocity of the fluid blowing the heated surface and the type of that fluid (air, water, oil). The convection process includes also the changes in the fluid density with the temperature, the viscosity and the motion of the fluid.

Newton's law of cooling gives a simple expression of the overall process of convection:

$$q = h_c\,A\left(T_w - T_a\right) \qquad (2)$$

where: q is the heat transfer rate by convection, [W];

h_c is the convection heat transfer coefficient of the material, [W/m^2 ·°C];

A is the surface of the heated body, [m^2].

T_w is the temperature of the surface (the wall);

T_a is the ambient temperature.

If the heated body is exposed to the ambient room air without any external source of movement, then the movement of the air is caused only by the density gradients near the body surface. This type of convection is called *natural or free convection*. If there is a fan blowing air over the heated body, then the process is called *forced convection.*

C. Radiation Heat Transfer

The physical mechanism of radiation heat transfer is different than the mechanism of conduction-convection heat transfer, where the heat is transferred through a material medium (fluid). The mechanism of radiation heat transfer is electromagnetic radiation and heat can be transferred even through a vacuum area. The heat transfer by radiation is described by Stefan-Boltzmann law of thermal radiation:

$$q = \varepsilon\sigma\,A T^4 \qquad (3)$$

where: q is the heat transfer rate by radiation, [W];

ε is the emissivity of the radiating surface;

σ is the Stefan-Boltzmann constant,

T is the absolute temperature, [K];

A is the radiating area, for magnetic components, this is the component open surface, [m^2].

The factor ε (emissivity) presents the ratio between the heat transfer rate q for a given surface and a black surface for which ε=1. Painted surfaces of almost all colors have the emissivity of about 0,9. The emissivity of a bright metal surface is much lower, about 0,05÷ 0,1.

In order to calculate the transformers performance with forced cooling several parameters and data sets are necessary:

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- *Transformer areas*

This will allow estimating how much heat can be dissipated to a frame by convection and radiation. On Fig.1 a EE core transformer is shown. Two different surfaces are used: one for convection (S_{conv}) and another one for radiation and conduction ($S_{rad}= S_{cond}$) heat transfer.

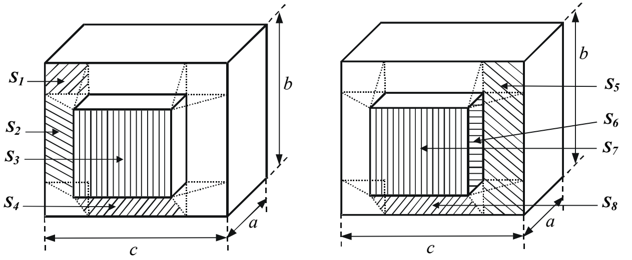

Fig.1 The equivalent surfaces of an EE core transformer

- Total distance of the boundary layer

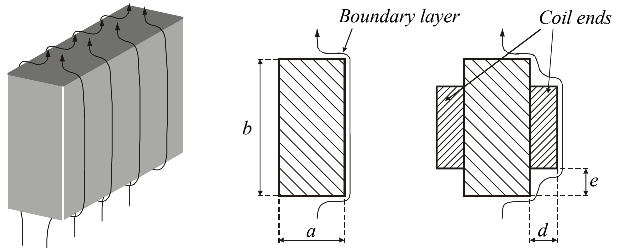

Fig.2 Parameter *L* as the total distance of the boundary layer: b) $L = a + b$; c) $L \cong a + b - 2e + 2\sqrt{d^2+e^2}$

A DC fan PMD1212PMB1-A, manufactured by SUNON is used. Air speed of 4.69m/s is obtained under the following conditions: air flow = 120CFM, circular outlet of the fan; no counter pressure. In the rough calculations 2.5m/s is used, because of the specifics of the equipment.

III. EQUATIONS OF THE HEAT TRANSFER FOR MAGNETIC COMPONENTS WITH FORCED COOLING

In the isotherm surface model (all open surfaces of the component have the same temperature) the total heat transfer rate *q*, which shows the heat dissipating capability of a component, can be presented as follows:

$$q = q_{rad} + q_{conv} \qquad (4)$$

where: q_{rad} , q_{conv} are the already discussed conduction, radiation and convection transfer rate:

$$q_{conv} = h_c S_{conv} \left(T_w - T_a\right);\ q_{rad} = \varepsilon \sigma S_{env} T^4 \qquad (5)$$

- Convection heat transfer with forced cooling

The improved equation for convection coefficient h_c is used [4]:

$$h_c = (3.33 + 4.8 u_\infty^{0.8}) L^{-0.288} \qquad (6)$$

where: *L* is the total distance of the boundary layer of the component, u_∞ is the speed of the air.

- Radiation heat transfer

$$h_R = \frac{\varepsilon \sigma \left(T_1^4 - T_2^4\right)}{T_1 - T_2} \qquad (7)$$

where: ε is the emissivity of the radiating surface;

σ is the Stefan-Boltzmann constant, $\sigma=5,67\times10^{-8} [W/m^2.K]$;

T_1, T_2 are the absolute temperatures of the hot body and the enclosing body;

The total emissivity ε of ferrites and the coating of nanocrystalline materials near 100°C is 0,95.

IV. DESIGN PROCEDURE AND EXAMPLE CALCULATIONS.

The design procedure is based on the “Fast Design Approach Including Eddy Current Losses“[5]. The example is based on nanocrystalline core F3CC-0050 FINEMET®. The heat transfer is calculated for natural cooling and for forced cooling using the fan PMD1212PMB1-A.

The obtained results are shown in Tables 1,3,4:

TABLE I

HEAT DISSIPATION CAPABILITY FOR NATURAL AND FORCED COOLING DESIGN

Maximum operating temperature	T_1	273+100	*K*
Ambient temperature	T_2	273+25	*K*
Air speed	*v*	2.0	*m/s*
Total area for convection	$S_{total,conv}$	13900	mm^2
Total area for radiation	$S_{total,rad}$	11600	mm^2
Total distance of the boundary layer	*L*	99.0	*mm*
Convection heat transfer coefficient of the material	h_C	22.7	m^2/C
Radiation heat transfer coefficient	h_R	8.2	m^2/C
Heat transfer rate by radiation	q_R	7.1	*W*
Heat transfer rate by natural convection	q_{NC}	6.8	*W*
Heat transfer rate by forced convection	q_{FC}	23.9	*W*

The results for the total heat transfer rate for the air speed of 2.0m/s are: without forced convection - *q=13.9W;* with forced convection - *q=31.0W.* The results show more than 2.2 times increase of the heat transfer with 2m/s. Figure 4 shows the heat transfer improvement (heat dissipation capability) as a function of the air speed across the component for speeds 0-5 m/s.

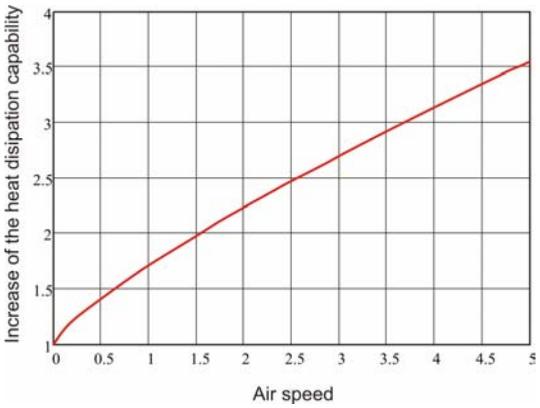

Fig.3 The heat transfer improvement as a function of the air speed across the magnetic component

V. OBTAINED RESULTS

Three welding transformers, based on one ferrite core (EE100/60/28 [6]) and two nanocrystalline cores (F3CC0025, F3CC0050 [1]), are calculated.

In the calculations natural air cooling is chosen for the first two transformers (F3CC0025, EE100/60/28) and forced cooling for the third one (F3CC0050). The welding transformer has the following input data:

TABLE II

INPUT DATA FOR THE TRANSFORMERS

Primary voltage	300V
Secondary voltage (no load)	60V
Secondary voltage (during welding)	26V
Secondary current (continuous)	150A
Working frequency	100kHz

All of the transformers are optimized in respect to obtain minimal losses and weight. The forced cooling is achieved with fan PMD1212PMB1-A. The chosen air speed is 2.5m/s.

TABLE III

LOSSES IN THE COPPER FOR EACH TRANSFORMERS.

	Losses				
	$P_{ohm,1}$	$P_{ohm,2}$	$P_{eddy,1}$	$P_{eddy,2}$	P_{total}
EE100/60/28	0,765	9,445	0,297	0,587	11,094
F3CC0025	1,010	3,247	0,590	2,939	7,786
F3CC0050	3,458	9,607	0,114	0,998	14,177

TABLE IV

COMPARISON BETWEEN THE DESIGNS

		Volume	Area	Total weight
		cm^3	cm^2	kg
Natural cooling	**EE100/60/28**	202,0	120,0	1,252
	F3CC0025	102,1	67,2	1,208
Forced cooling	**F3CC0050**	78,6	53,0	0,793
Improvement - nanocrystalline vs. ferrite (natural cooling)		49,5%	44,0%	3,5%
Improvement - natural vs. forced cooling (nanocrystalline)		23,0%	21,1%	34,4%
Improvement - best scenario		61,1%	55,8%	36,7%

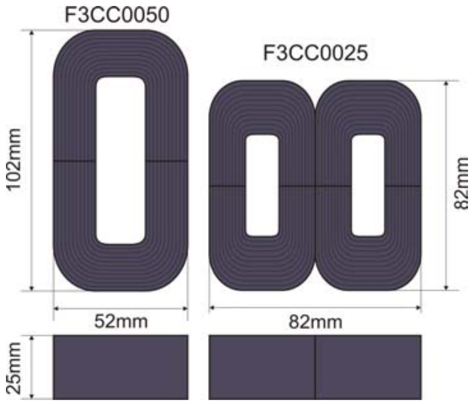

Fig. 4. Dimensions for the used nanocrystalline cores.
Left - F3CC0050 core (2 pieces), Right - F3CC0025 (4 pieces)

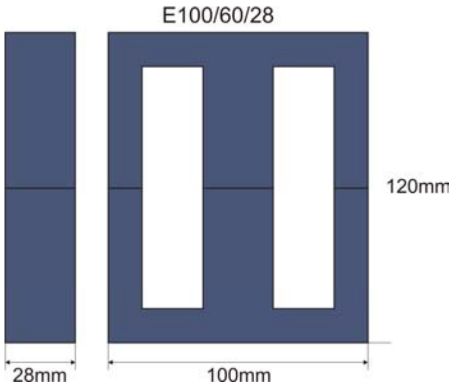

Fig. 5. Dimensions for the used ferrite core EE100/60/28 (2 pieces)

VI. CONCLUSION

A design approach is proposed for dimensioning magnetic components with forced cooling. The heat transfer is applied considering the specifics of power electronics magnetic components. Two different surfaces: one for convection (S_{conv}) and another one for radiation and conduction (S_{rad}) are used to calculate heat transfer rate, as well as a boundary layer length. A step-by-step design procedure is proposed including calculations of the heat transfer with a given fan and its parameters. A practical example transformer based on nanocrystalline cores is calculated, built and measured under forced and natural cooling.

The design results and experimented transformers show the following improvements:

- Using a nanocrystalline core instead of classical ferrite cores results in 50% in volume and 4% in total weight of the component.
- Using forced cooling provides 23% in volume and 34% in total weight.
- The best improvement (ferrite with natural cooling vs. nanocrystalline with forced cooling) is more than 2.5 times in volume and 37% in total weight.

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