TITLE: Modelling of temperature dependence of saturation magnetisation of silicon-iron steels

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ABSTRACT BODY:
Digest Body: ***Abstract-***The temperature dependence of saturation magnetisation of commercial 0.1 to 3 wt. % silicon steels is first measured using an air-cored solenoid and then modelled using a linear formula in accordance with the spin-wave theory, over the range of 20-100°C and in 100 KA/m applied field. The samples measured were heated by applying a heavy ac current along their length, and the measurement of temperature was made using thermocouples. The paper discusses the effect of temperature variation on magnetisation in high field regime approaching saturation in several grades of electrical steel.

Introduction
Saturation magnetisation is a structure-insensitive property of silicon-iron steels. It, unlike other characteristics, is usually unaffected by the fabrication or heat treatment of the steels and changes only slowly with their chemical composition and temperature [1].
The temperature dependence of saturation magnetisation of silicon-iron steels has been under intensive investigation for many years. Most of the studies were mainly concerned in the range below room temperature. Antonini measured spin-wave dispersion relations in Fe0.93-Si0.07 and Fe0.85-Si0.15 steels by means of the so-called diffraction method in conjunction with polarised neutrons at room temperature [2]. Using FMR and FMAR methods, the saturation magnetisation of 3% silicon-iron single crystals was measured between 3.5 and 300 K [3]. Graham [4] presented measurements only at two points below room temperature (*77* and *195°K*), and Argyle et al [5] in the region *4-29°K* only. The stiffness constant was found to decrease with the decrease of Curie temperature or the increase of silicon content in silicon-iron steels [2, 6-8].
Empirical studies show that for temperature lower than a third of the Curie temperature, T_C, the temperature dependence of saturation magnetisation of silicon-iron steels can be described according to the spin-wave theory [10, 11, 12] by:

$M_S(T) = M_S(0) - B_1 T^{-3/2}$ ....(1)

with

$B_1 = \zeta(3/2)[g\ \mu_B]\ (KB/4\pi D)^{3/2}$ ....(2)

where the Riemann zeta function $\xi(3/2)=2.612$ [5]. μ_B is Bohr magneton (9.27×10^{-21} *emu*), Boltzman constant (8.61×10^{-5} *eV/K*), and the Lande factor (≈2.1). In this paper, the sample temperature is changed from *20°C* to *100°C*, and, in this range of temperature, the spin-wave stiffness constant of equation (2) is assumed temperature independent. The above equations provide a model for temperature dependence of saturation magnetisation. The results obtained using this model is compared with measurements carried out on an experimental set-up which allows high field magnetisation near saturation in samples of non-oriented and grain-oriented electrical steel strip.

Experimental Set-up and Measurements
The samples that were cut into the Epstein size from their original silicon-iron sheets. These included the mostly widely used 0.1-1.8 wt. % silicon non oriented steels and 3 wt. % silicon grain oriented steels. Compositions of these samples were determined using the precise chemical analysis. Cross-sectional areas are determined from the lengths, weights and densities of the samples. Densities are in turn determined from the silicon and aluminium contents of the samples in accordance with British standard [13]. All the samples were in final annealed state. Fig. 1 shows the experimental set-up which consisted of an ac excited long air-cored solenoid, used to measure saturation magnetisation of the Epstein samples. Air flux inside the B-coil, located at the centre of the solenoid was compensated using a variable mutual inductor [14]. Saturation magnetisation of the samples was measured using a 0.1% average-type precision multimeter. To saturate the sample, the peak value of the external magnetic field was well in excess of *100 KA/m*. To estimate the precision value of the conventional formula deduced from above equations, the measured temperature dependence of saturation magnetisation are plotted in Fig. 2. The calculated values are also shown in this figure using solid lines.

The results shows that temperature dependence of saturation magnetisation of the steels investigated in the temperature range of *20-100°C* can be modelled using the conventional linear formula, having experimental confirmation with a standard deviation of less than *0.12%*.

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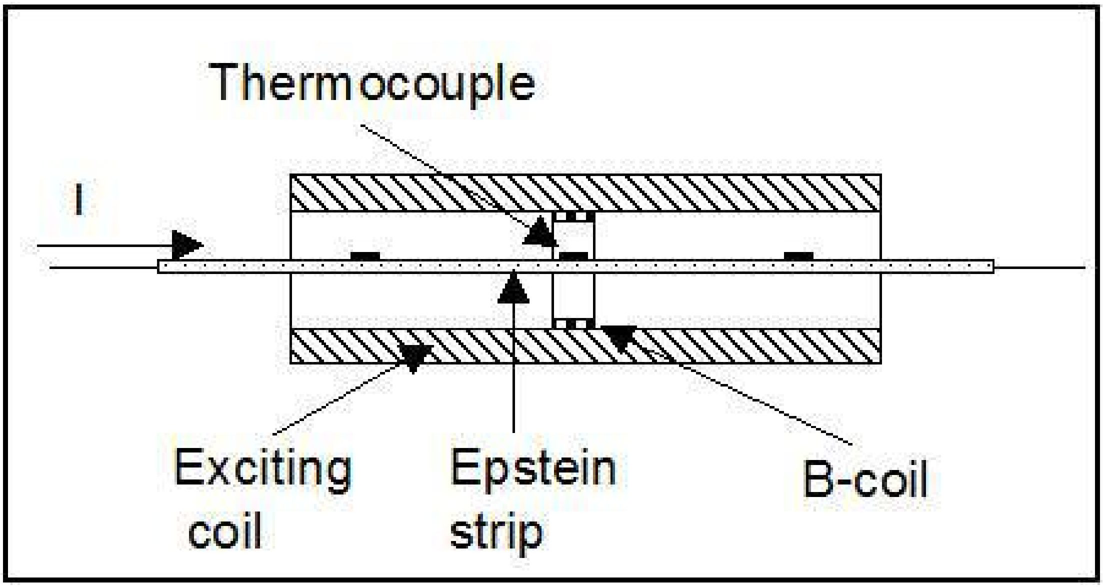

Fig. 1 A simple experimental set-up for the measurement of saturation magnetisation of silicon-iron Epstein strips.

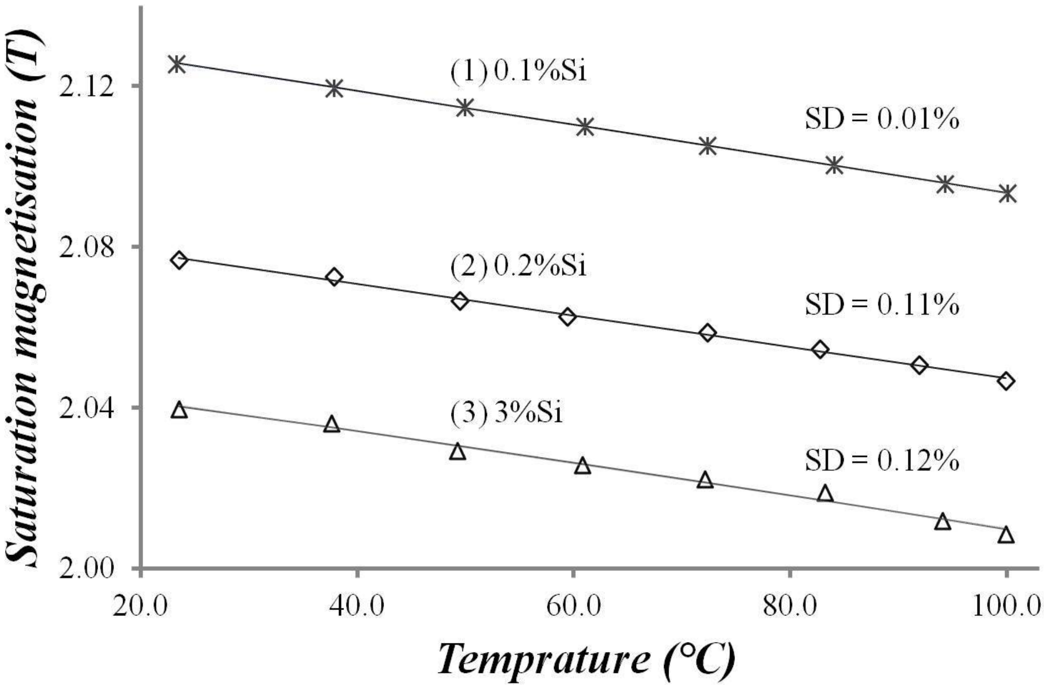

Fig. 2. The temperature dependence of saturation magnetisation of 0.1, 0.2 and 3.0% silicon steels.