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Skin Temperatures of Animals and Thermal Convection of Air under Magnetic Fields

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Abstract

We demonstrate by flow visualisation experiments that free thermal convection can be substantially modified in the presence of inhomogeneous magnetic fields (H) and outline the underlying physical mechanism. It involves overcompensation of the convection driving gravitational force by the magnetic force χH grad$H$ on paramagnetic O_2 molecules occurring even in the modest fields of a standard pole piece electro-magnet. This effect may fully account for the recently reported field induced skin temperature changes in animals.

1. Introduction

Recently magnetic field induced skin temperature changes of up to about 5°C in fields around and above 2 Tesla have been observed in man [1], mice [2] and homing pigeons [3]. The work on mice and pigeons most clearly reveals the importance of the *gradient* of the magnetic field (grad$H$) rather than its absolute field value (H), since the induced temperature change (ΔT) (including its sign) depends on the location of the probe on the pigeon [3], and on the position of the animal with respect to the center of the solenoid [2, 3]. The physical and/or physiological origin of these a priori alarming effects remained unclear. In this paper we demonstrate that magnetic field gradients such as those used in the above work cause substantial changes of the convective motion of air around the warm body. We provide evidence that this mechanism accounts for all temperature effects observed on pigeons.

2. Results

We have performed temperature measurements and flow visualisation experiments in various simple vertical convection cells (without pigeon) inserted into two different Bitter-type solenoidal magnets and a pole-piece magnet. The results obtained with the vertical 45 mm diameter split coil magnet were reported elsewhere [4]: Within the cocylindrical convection cell used (having a central copper tube kept at 50°C and an outer cylinder at 20°C), the changes of the air temperature under magnetic field turned out to be very similar in magnitude and time dependence to those found on the pigeons skin. Second, filling the convection cell with pure oxygen gas increased the field induced temperature offset (ΔT) whereas it was suppressed below the limit of resolution (≈ 0.1°C) under pure N_2 or Ar atmosphere or under vacuum [4]. This demonstrates the importance of O_2 in the process. Note that O_2 is the only paramagnetic substance present to any significant amount in ambient air. Third, for both pigeons [5] and convection cell [4] ΔT was found approximately proportional to the radial temperature gradient ($\mathrm{d}T/\mathrm{d}r$) which could be reduced to zero by setting the temperature of the outer housing equal to the temperature of the pigeons body or the central tube, respectively. Finally the variation of ΔT as a function of the vertical position (z) inside the solenoid is directly related to the z-dependence of H grad H.

Figure 1 shows the z-dependence of H and H grad H of the 16 cm bore vertical Bitter solenoid used for the experiments both with pigeons [3] and with the large cocylindrical convection cell reported here. The outer diameter of the central tube (50°C) of the convection cell was 32 mm and the inner diameter of the outer tube (20°C) was 127 mm. The cell was inserted into the solenoid and closed at $z = 45$ cm and $z = -65$ cm above and below the magnetic center of the solenoid ($z = r = 0$). It can be seen that the force f_m attracting O_2 molecules into regions of higher magnetic fields (given by $f_m = \chi_m H$ grad$H$, with χ_m being the molar paramagnetic susceptibility, $\chi_m = 3.45 \times 10^{-3}\,\mathrm{cm^3\,mol^{-1}}$ of O_2) becomes more than one order of magnitude larger than the gravitational force M g. M denotes the molar mass of O_2, g is the gravitational constant. Thus O_2 molecules are attracted from below and above into the central plane of the solenoid. This results, at first, in an increase of the O_2 density ϱ in the central region of the solenoid, but as the total magnetic energy acquired (with respect to large z) $\int f_m\,\mathrm{d}z \approx \chi_m H^2$ is much smaller than the thermal energy kT even in fields of ≈ 10 T, the relative change in $\varrho(z)$ is smaller than about 0.1%. The fact, however, that $f_m > M$ g has a dramatic effect on thermal convection. Convective motion is driven by the *difference* between the forces on neighboring volume elements of air. The horizontal temperature gradient $\mathrm{d}T/\mathrm{d}r$ causes both a horizontal density gradient $\mathrm{d}\varrho/\mathrm{d}r = -\alpha\varrho\,\mathrm{d}T/\mathrm{d}r$, ($\alpha$ being the coefficient of thermal expansion), and a horizontal gradient of χ_m (as $\chi_m = C/T$, C being the Curie constant). This results in a r dependence of the pressure gradient $\mathrm{d}P/\mathrm{d}z$:

$$\mathrm{d}P/\mathrm{d}z = -\alpha\varrho\,\mathrm{d}T/\mathrm{d}r\; r[\mathrm{g} + (\varrho_0/\varrho)2\alpha C\,H\,\mathrm{grad}\,H/M] \qquad (1)$$

ϱ_0 is the O_2 density and we put $\chi_m \approx \alpha C$. This pressure can obviously not be balanced by the same hydrostatic pressure everywhere in a plane z = const. Therefore instability to convective motion must occur. In a high aspect ratio vertical cell (at $H = 0$) convection sets in at very small $\mathrm{d}T/\mathrm{d}r$ [6], the air rising along the warmer central tube and falling along the colder outer tube thereby forming a single convection roll. Under strong field ($f_m > M$ g) the net force is opposite to g in the region below the magnetic center ($z < 0$) and hence air falls along the warm wall and rises along the cold wall, whereas in the region $z > 0$ the sense of rotation of the roll does not change. We expect therefore a two roll convection pattern in this solenoid under field. Our position dependent temperature measurements and visualis-

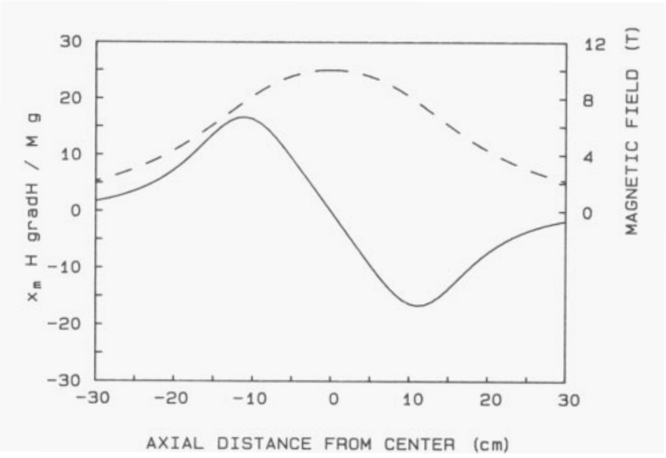

Fig. 1. Axial magnetic field profile (– – –) and force on a paramagnetic O_2 molecule (——) in a vertical Bitter-type solenoid.

ation using smoke [4] performed in a split coil solenoidal magnet were in agreement with this mechanism and have indicated that the flow is controlled by the spatial variation of f_m.

Figure 2(a) shows the result of a visualisation experiment in a pole piece magnet which, because of the geometry allowing to photograph the complete roll pattern, most directly demonstrates the magnetic field induced modification of the convection. A rectangular high aspect ratio convection cell (width 0.6 cm, height 7.6 cm, depth 0.4 cm) with its left wall cooled to 16°C and its right wall heated to 31°C (Fig. 2(c)) was inserted between the poles of a conventional electromagnet. The field profile measured along a central vertical line is given in Fig. 1(d). The dip in field near the center results from a horizontal bore in the poles (parallel to H) not visible on the photographs. Note the two additional sign reversals of H grad$H$ in comparison to the profile shown in Fig. 1. Injecting a small amount of cigarette smoke with a syringe through an orifice at the bottom of the convection cell reveals, first, the existence of one simple convection roll in zero field (Fig. 2(a)). When applying a field of only 1 T (Fig. 2(b)) a dramatic change of the convection pattern appears within several sec: Four convection rolls can be clearly distinguished, the observed sense of rotation being indicated in Fig. 3(c). The lowest roll rotates like the roll at $H = 0$ as in this region $f_m < M$ g. The same applies to the uppermost roll but it extends more into the high field region because in this region f_m and g are parallel and add. The second lowest roll rotates in opposite direction; in this region f_m overcompensates M g. The existence of the third lowest roll is related to the dip. In fact in this region H grad$H$ is just not large enough ($f \approx M$ g) for the two additional rolls expected in strong fields to appear. Rather only the lower one develops because for this one f_m and M g are parallel whereas f_m and M g essentially cancel for the upper one.

This experiment clearly demonstrates that fields in the Tesla range are sufficient to completely modify convection patterns in air (provided the existence of field gradients similar to those typical for standard pole-piece magnets). Since in a solenoid $f_m \sim H^2$, the convection driving forces may even become large enough (in fields of order 10 T) to provoke turbulent convection [4].

3. Discussion

In principle the laminar convective velocity pattern under field could be calculated by solving simultaneously the corresponding hydrodynamic and thermal transport equations with proper boundary conditions. In order to obtain a rough estimate of the main features of the flow pattern we rather apply the following simple procedure: For our experimental parameters we estimate that in the zero field the inertia term in the Navier-Stokes equation is about 2 orders of magnitude smaller than the viscous term; in addition the major component of f_m is along z. Therefore we put the z-component of the local velocity $v_z(r, z)$ proportional to the local value of $\mathrm{d}P/\mathrm{d}z(r, z)$. We also suppose that the radial density and temperature profile are not modified by the flow, i.e., they are assumed independent of z. This is obviously very crude as the experimental temperature profile $\Delta T(r, z)$ appears modified.

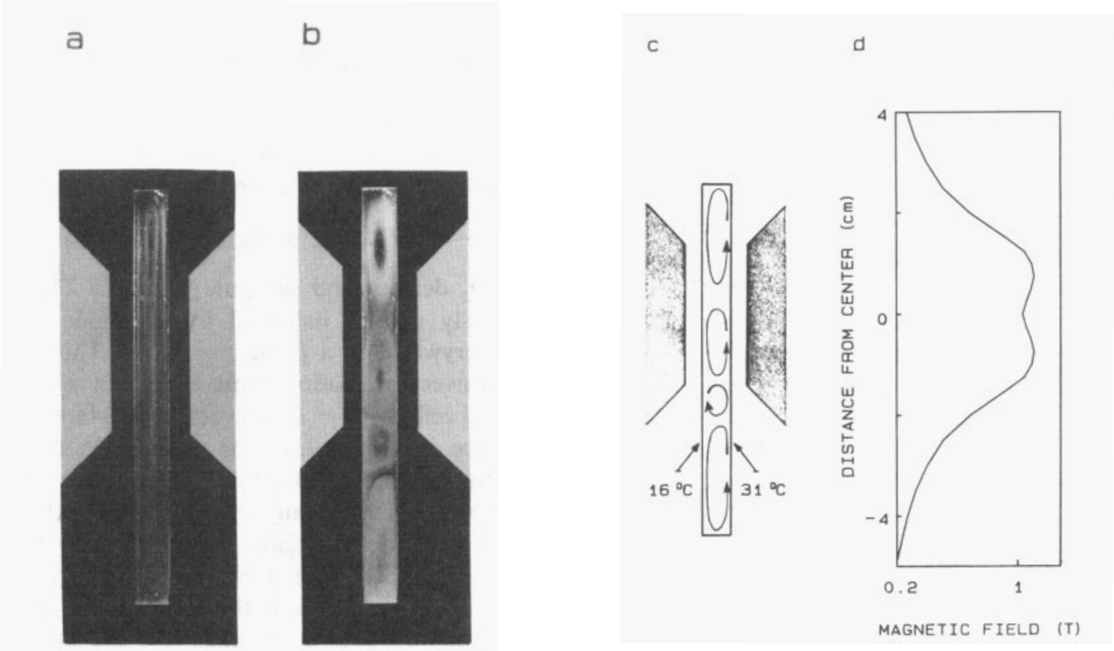

Fig. 2. Photographs of the flow pattern in a vertical thermal convection cell visualised by cigarette smoke. (a) Magnetic field off, (b) magnetic field on, with the field profile given in (d). The sense of rotation and the convection rolls in (b) are schematically indicated in (c).

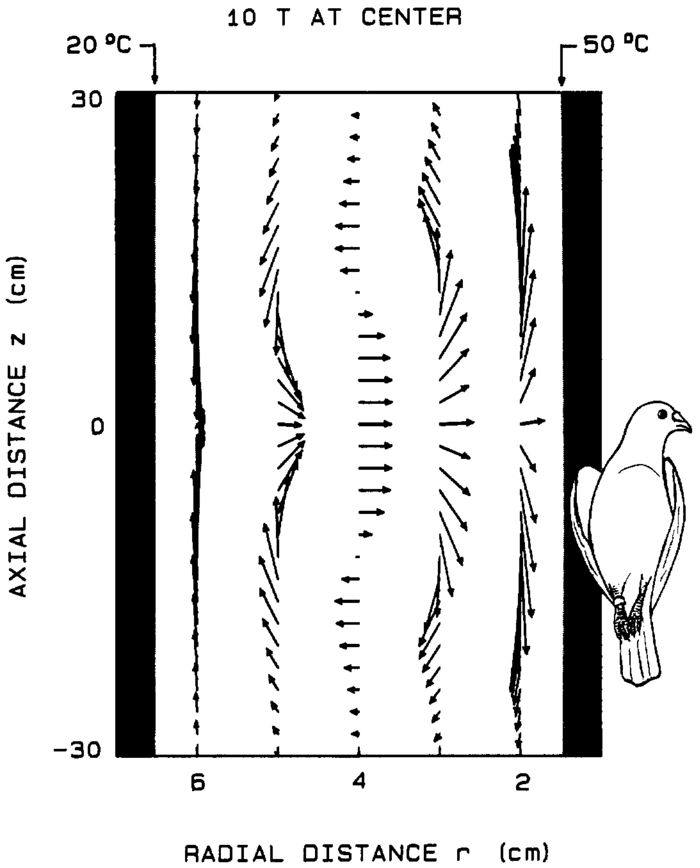

Fig. 3. Calculated map of the flow velocity in a cocylindrical convection cell inside the solenoidal magnet having the field profile given in Fig. 1. Details are reported in the text.

But as long as ΔT is much smaller than the temperature drop across the cell the corresponding effect on the flow pattern may be considered as a second order correction. Using these assumptions and using $V_v = 0$, we can directly calculate the velocity maps $v_z(r, z)$ and $v_r(r, z)$ from the force map $f_m(r, z) + M g$ at any point (r, z). f_m stems from a calculation of H grad$H(r, z)$ for the large solenoid (Fig. 1) which was carried out by G. Aubert. The resulting calculated flow pattern in $H = 10$ T for the large convection cell is shown in Fig. 3. The expected two roll convection pattern appears very clearly. At locations of radial inward, or outward flow (as compared to the case $H = 0$) the local air temperature will be smaller, or larger, respectively than the zero field value.

Introducing a pigeon into the cell instead of the thin central warm tube certainly somewhat modifies the boundary conditions and the convective flow pattern is harder to estimate. However since the magnetic field effect on the flow pattern, and hence on the local heat transport, is essentially controlled by the local values of f_m, as revealed for all three magnets and convection cells used, the field effect on the local temperature near the pigeon skin should be very similar to the one evident from Fig. 3.

In conclusion the mechanism outlined above may account for the magnetic field induced temperature changes in pigeons. It is consistent with the observed lack of magnetic field effects on other physiological parameters in pigeons [4]. It may also account for the skin temperature changes observed in man [1] and mice [2], and may eventually be at the origin of other yet unexplained magnetic field effects on living systems. The described effect may lead to interesting (non-biological) applications.

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