European Journal of Physics

PAPER

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To cite this article: M Bertò *et al* 2014 *Eur. J. Phys.* **35** 025016

IOP Publishing European Journal of Physics

Eur. J. Phys. **35** (2014) 025016 (12pp) doi:10.1088/0143-0807/35/2/025016

'Climate change in a shoebox': a critical review

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Received 11 October 2013, revised 6 January 2014
Accepted for publication 5 January 2014
Published 31 January 2014

Abstract

The laboratory replication of the greenhouse effect appears deceptively simple. Using a cubic box illuminated by an ordinary lamp, one may show some of the phenomena present in the climate system. It is nonetheless necessary to use a lot of physical ingenuity to understand the complex interaction of radiative and convective phenomena which characterizes such a simple system. In this paper we introduce a critical review of some experiments in the literature and suggest a new and original experimental set up using an unusual gas; in this way we overcome some of the limitations of the typical laboratory experiment, confirming the possibility of using it in educational physics laboratories without any lack of physical plausibility.

Keywords: greenhouse effect, educational laboratory experiment, convection, radiative absorption, carbon dioxide, nitrous oxide

(Some figures may appear in colour only in the online journal)

1. Introduction

Public awareness of science is a very important topic and its importance is even greater when the practical consequences of science play a crucial role in our life and future. This is the reason why specific topics and phenomena such as global warming (GW), one of the main topics of modern climatology, possess an enormous attractive potential for students, teachers and the general public. One consequence is the passionate search for simple but rigorous experiments capable of showing the behaviour of such phenomena. Physics teachers have a great responsibility to merge simplicity and correctness, with the aim of not damaging both students' and the general public's confidence in science and in the scientific method. A partial

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or even incorrect approach in a laboratory or theoretical presentation of a certain topic may have very negative consequences, not simply on its educational content but also on the image of science itself and on the trust we put in it.

This why the criticism raised by a recent paper [1] regarding the most common laboratory experiment which presents the greenhouse effect to students, the ‘greenhouse in a shoebox’, using the limited and simple procedures illustrated in the literature [2–6] is of great importance and has focused our interest.

2. A short review

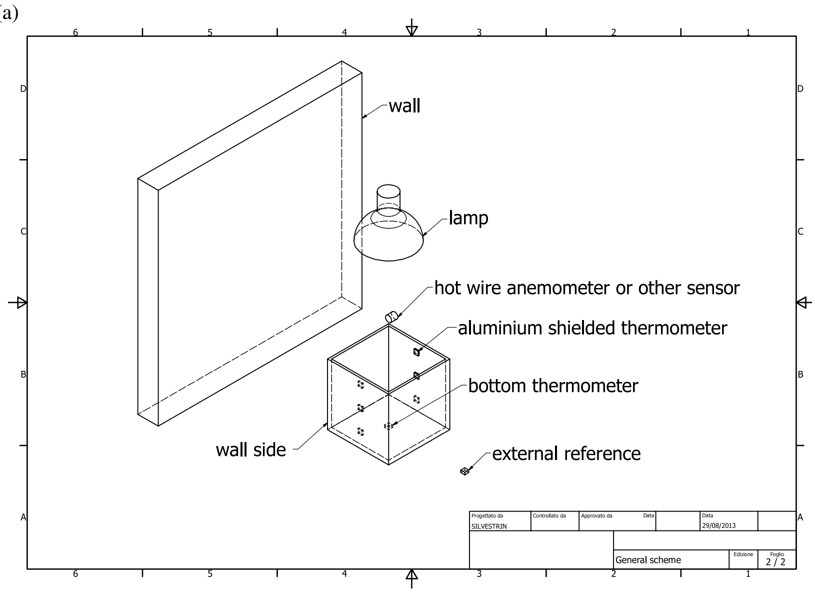
Several of the articles describing the usual experiments used to reproduce the greenhouse effect are not, in general, sufficiently accurate regarding the experimental apparatus and the measurement procedure, as well as the data analysis and the modelling of the experimental apparatus. The experiments described in the literature [2–6] are based on an experimental apparatus consisting of a vessel illuminated by a light source, such as a bulb. The vessel can be either closed, such as a plastic bottle, or open, such as a simple box open at the upper end. The typical procedure consists in illuminating the vessel and then waiting until the equilibrium temperature is reached. Then the air in the vessel is displaced by introducing carbon dioxide and an increase of the temperature of the vessel is observed. A typical scheme of the experimental apparatus is shown in figure 1(a).

Some articles [5, 6] suggest producing the carbon dioxide directly within the vessel by the reaction of some spoonfuls of bicarbonate of soda with vinegar. This chemical reaction releases carbon dioxide, but this practice is probably not appropriate as the chemical reaction is endothermic and can affect the temperature measurements. Generally, a significant increase in the temperature of the carbon dioxide is observed. This temperature change is attributed to the phenomenon that causes global warming. In many articles infrared radiation is not even mentioned. The authors only say that the rise in temperature occurs due to the greenhouse effect. In particular, experiments which use plastic bottles may be more appropriate for discussing the absorption of infrared radiation by the carbon dioxide than the greenhouse effect [5]. The generally given interpretation is that the visible radiation of the lamp passes equally through the carbon dioxide as through the air and that, instead, the infrared radiation is absorbed by the carbon dioxide thus causing the heating. In [3], placing a small slab of dark material inside the bottle is suggested in order to absorb the incident visible radiation and enhance the emission of infrared radiation.

In [1], the typical interpretations of the experiment given in the other articles are refuted. The authors state that the increase in temperature observed after the input of the carbon dioxide inside a vessel open at the top and illuminated by a lamp is partly due to the absorption of infrared radiation, but mainly due to the blocking of convective motions and the associated heat transfer. The blocking of convective motions is caused by the density of the carbon dioxide which is greater than air density. Before proposing a simple linear model to support this interpretation, the authors suggest trying the experiment using argon instead of carbon dioxide. Argon has a density greater than air (and thus it remains within the open vessel) but, unlike carbon dioxide, it is not a good infrared absorber.

The important result of [1] is certainly the experimental comparison of the effects of argon and carbon dioxide, which, in the opinion of the authors, appear ‘almost identical’ (as shown in figure 2 of [1]) and thus they claim that the temperature effect caused by argon must be due to causes other than radiative absorption, i.e. convection blocking.

(a)



(b)

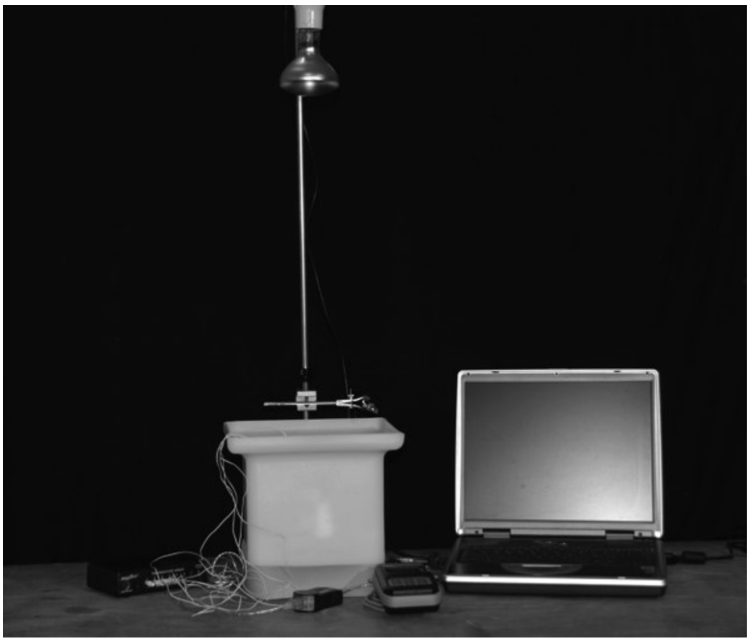


Figure 1. (a) The experimental apparatus: a general scheme. (b) The experimental apparatus: our effective design.

However, some experimental details appear questionable: is it possible that carbon dioxide, which is not only denser than argon but has also a radiative absorption effect, gives a temperature increase 'almost identical' to argon? How many experimental runs have actually been compared? If convection is so important, what is the role of the actual position of the thermometer (shown in figure 1 of [1]) which is not at the bottom of the vessel?

On the other hand, the theoretical steady state analysis of [1] regarding the temperature increase is convincingly performed in a simple linear form with some numerical comparisons of the two different effects: convection and radiative absorption. That analysis would better be performed considering gases with completely separated effects, but carbon dioxide, however, has a double effect. As a consequence of this consideration, it would be interesting to compare carbon dioxide not only with a non-radiative absorbing gas such as argon, but also a different and powerful radiative absorbing gas, possibly with the same convection blocking effect (or in other terms with the same or a very close density).

The atmospheric greenhouse effect can be modelled at different levels of detail and there is a broad literature describing its physical basis. A lot of models also exist from a computational point of view which allow the description of the greenhouse effect and are able to reproduce the effects due to changes in the concentration of greenhouse gases in the atmosphere of the global climate system. Owing to the complexity of the climate system, it is clear that some approximations must be made which correspond to the limits of the model or theory used (e.g. the use of climate models of different dimension number); a similar situation also pertains to the case of laboratory experiments on the topic.

In this work the 'classic' experiment to reproduce the greenhouse effect for teaching purposes in a physics laboratory is analysed in depth with regard to several aspects with the aim of confirming or disproving the considerations made in [1].

The experiment is defined more precisely and its conditions and limitations are shown; moreover, using a larger set of gases (air, argon, carbon dioxide and nitrous oxide) with different densities and spectral absorptions, it is possible to experimentally show the actual role of the radiative greenhouse effect. In particular, considering that the density of carbon dioxide and nitrous oxide are very close, the differences in their behaviour can only be due to the differences in their infrared spectrum. Nitrous oxide has a greater ability to capture infrared radiation then carbon dioxide, so it should show a greater increase in temperature.

Using this experimental strategy and a large number of runs, we show that the 'classic' experiment may be performed with good results, showing the effects of both convection and infrared absorption.

A significant point to consider is that the reciprocal interactions of convection and radiation in the heating of a cavity are considered in the specific literature of heat transfer, as the 'square enclosure', 'square cavity' or 'shallow open cavity' problem. Given its role in many practical applications such as the cooling of electronic circuits or similar situations, this problem has rarely been analysed experimentally, in most cases it has been analysed by numerical simulation. Some general conclusions may be extracted from a survey of the literature [7 and references therein] and they will be discussed very briefly in section 4. It is also worth noting that even in this topic, no experiment or numerical simulation identical to the experiment we are considering has been analysed.

A final consideration is that the general scheme of the experiment is extremely close to a natural phenomenon described in a very particular location, the 'Bossoleto spring', a natural carbon dioxide source near Siena, Italy. Bossoleto is a natural, circular depression, with a depth of some meters and an area of 4000 m^2 (thus with a size ratio very different to the common boxes) which is fully replenished each night with carbon dioxide and then, during the early hours of the day, is depleted by the action of heating by the Sun, with convection and infrared absorption quite reasonably playing an important role. A short description of the phenomenon may be found in specialized literature [8]. Bossoleto has been used as a model for the consequences of GW and an increase in carbon dioxide concentration on plant growth.

3. Materials and methods

The experimental apparatus is shown in figure 1(b). Some other practical details will be given in the text.

3.1. Materials

The materials we have used to perform the experiment are generally similar to those proposed in the literature and they are commonly found in teaching laboratories.

Here is a short list of the materials used in the experiment with their main characteristics:

- a (20 × 20 × 20) cm vessel made of 'Nalgene®' (high density polyethylene);
- a 150 W incandescent lamp (Philips® reflector) with a light concentrator; while its spectrum is different from the Sun's spectrum, its general characteristics are reasonably well known: it emits about 11% of its power in visible radiation, while its emission in infrared may be roughly estimated from the temperature of the glass bulb.

3.2. Experimental procedure

Thermal sensors (thermistors, resolution 0.01 °C), characterized by a very low thermal capacity and shielded from direct exposure to the lamp using thin aluminium foil, were placed at various heights and on the bottom of the vessel. We measured the temperature using a 2 Hz sampling frequency. At the beginning of the experiment, we always checked that the vessel was at 'thermal equilibrium' with the room, a stable state corresponding to the short horizontal line at the extreme left in figure 2. A shielded sensor simultaneously measured the temperature of the environment at a significant distance of about 1.5 m from the vessel in order to eliminate cross effects. This external sensor works as a constant external reference. To eliminate the effect of uncontrolled air movements, the laboratory air-conditioning device was turned off, and this had the effect of a slow but constant drift of room temperature during the day. We must thereby subtract the value of the environment temperature at any given time from the in-box measurements.

Once we obtained the stable state (generally after 100–200 s), we lit the lamp (positioned 73 cm from the bottom of the vessel, see figure 1(b), the distance was chosen for practical reasons) and centred on the bottom of the vessel. At this time, the temperature at the bottom of the vessel and that measured on the walls begin to rise rapidly, following a pattern typical to heating and cooling phenomena (figure 2).

After a time of the order of 6000 s, the system reached a new stable state and the temperatures of the bottom and the walls of the vessel stabilized around a new plateau value. At this time, we began to check the presence of air movement and the air speed with a hot-wire anemometer (resolution 0.01 m s^{-1}) located on top of the vessel, see figure 1(b).

To ensure that the vessel was completely full, we previously bubbled the various gases in a buret over water in the same input conditions. However, in the case of argon and carbon dioxide, the complete filling of the vessel can be checked using a naked flame. While the system reached the equilibrium, we filled a large plastic bottle with the first gas that was to be added to the vessel.

After a thermalization of about 15 min, the gas was introduced inside the vessel using gravity. The thermalizing step is essential to reduce excessive cooling due to the new gas, recently expanded at environmental pressure from its cylinder or lab pipe. Being denser than air, the new gas tended to stay inside the vessel unless there were strong convection movements. The input of new gases caused a further rapid increase in temperature which

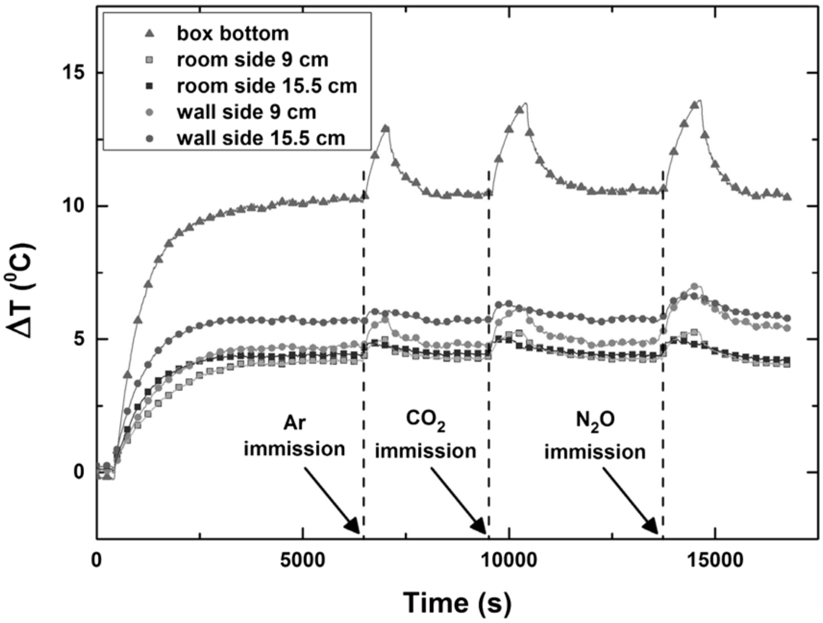


Figure 2. Typical behaviour of the temperature at the bottom (triangles) and at two different heights on two opposite sides (black circles, 15.5 cm, grey circles, 9 cm, on the wall side, black squares, 15.5 cm, grey squares, 9 cm, on the lab side) of the box at the indicated heights; the different steps of the experiment and the introduction of the three gases are shown.

stopped abruptly after about 5–600 s. The natural convective motions that were established within the vessel caused the gas to come out and to be replaced by the (colder) outside air at a certain temperature. The temperature therefore started to decrease until it again reached the previous plateau temperature (the gas was completely released into the environment).

This working cycle was repeated with the same insertion order for argon, carbon dioxide and nitrous oxide. For the latter gas, it was necessary to wear a self-contained breathing apparatus (SCBA). An interval of 2000–3000 s separated each new gas input in order to allow the complete spontaneous reintroduction of the external air.

After some initial experiments to establish the basic conditions, the complete four-gas procedure was repeated 20 times, enough to consider the measured values as an acceptable statistical sample (see section 4).

The analysis of the convection phenomenon required a detailed knowledge of the temperature as a function of height on the wall. For this reason, we performed some experiments with twelve sensors placed symmetrically on the walls (three per wall) at various heights and others in which there were eight sensors placed on a single wall about 1.5 cm from each other.

To show the block of convection confirming the anemometer results directly, we used some silk threads (silk fibres deprived of the soluble portion) kindly provided by the University laboratory ‘BIOthech’ based in Mattarello (Trento). Some of the threads were attached at one end to a rod which was been hooked at the upper edge of the vessel.

In order to test the hypothesis that the fluctuations present in the temperature measurements were due to the movement and detachment of small bubbles of hot air close to the bottom, in some experiments the bottom temperature was measured using a fast response thermocouple (response time 0.001 s) [9], which is able to distinguish the noise variation always present in the system and the slower convection bubbling due to the warming from the lamp.

Moreover, in order to fully absorb the visible radiation emitted by the lamp, we performed some experiments in which we placed an approximately 0.5 cm thick layer of graphite powder on the bottom of the vessel. This modification does not appear to strongly modify the final results, probably because the roughness of the bottom may increase the role of convection.

Finally, to reduce the effect of the thermal inertia of the table (which was in contact with the vessel bottom), the box was not placed directly on the table but on four plastic supports, and the movement of external air was reduced (but not excluded) using pieces of cardboard (figure 1(b)).

4. Results and discussion

The typical experimental results are shown in figure 2.

One can follow the temperature variation during the experiment at the bottom of the box (triangles) and at two different heights on two opposite sidewalls of the box. The side of the box closer to the wall of the laboratory shows a difference in temperature at 15.5 cm (black circles) and 9 cm (open circles). The side facing the room (black squares, 15.5 cm, and open squares, 9 cm) shows no meaningful difference between the two heights. This difference between the two sides is an indication of the sensitivity of the experimental system.

An initial, general, comment is that in our experiments as well as those of Wagoner *et al* (see figure 2 of [1]), no steady state temperature is attained after the input of a new denser gas. This is a strong indication that, with such an experimental design, the gas expansion, the diffusion and the convection movements become, at a certain times, able to force gases out of the box. However, we note that in some experiments performed in our lab with a different geometry of the box (higher height to base area ratio; not discussed here) the stable state was effectively attained, so the effectiveness of the convection block could depend on the geometry of the vessel. In the Bossoleto phenomenon, with a very low height to base ratio, convection mixing is very strong and rapidly effective; it is reasonable to consider that with a very high height to base ratio, the convection block is stronger and convective phenomena would be unable to expel the gases from the vessel and so an effective stationary temperature state could be reached. This effect could properly be considered as a 'greenhouse-without-walls' effect. A further consideration is that, if no steady state is attained after the input of a new gas, quantitative considerations based on steady state analysis are only approximate.

Our final results of the bottom temperatures and their statistical analysis are shown in tables 1 and 2. We recall that these are the temperature gaps between the state of the system with air or before the introduction of a denser gas and the peak value obtained immediately before the spontaneous temperature reduction. The values are normally distributed in each set (after the Shapiro–Wilk test) and, applying the Student's *t*-test, a *p*-value less than 0.0005 is obtained for the comparison of carbon dioxide and nitrous oxide with argon and for carbon dioxide with nitrous oxide. As a consequence, one can confirm that there are significant differences among the effects of the three gases; moreover, the effects of the three gases remain in the order $Ar < CO_2 < N_2O$.

Conclusively, the difference due to a purely convective effect corresponds to the difference found between air and argon, 2.64 °C, while the effect due to a purely radiative absorption effect (but correlated with the different spectra of carbon dioxide and nitrous oxide) is 0.25 °C. Later we will comment on the details of spectra differences.

Table 1. Values of the maximum temperature increase caused by Ar, CO_2 and N_2O with respect to air and measured by the sensor positioned on the bottom of the vessel in 20 different runs.

Exp. Num.	(ΔT Ar $\pm$ 0.01) (°C)	(ΔT CO_2 $\pm$ 0.01) (°C)	(ΔT N_2O $\pm$ 0.01) (°C)
1	2.34	3.06	3.46
2	2.44	3.20	3.23
3	2.69	3.29	3.56
4	2.57	3.20	3.48
5	2.53	3.42	3.54
6	2.72	3.07	3.50
7	2.84	3.55	3.90
8	2.98	3.51	3.81
9	2.88	3.67	3.99
10	2.63	3.08	3.53
11	2.52	3.07	3.32
12	2.32	2.98	3.24
13	2.61	3.32	3.45
14	2.69	3.55	3.75
15	2.73	3.51	3.58
16	2.31	3.02	3.31
17	2.77	3.36	3.46
18	2.64	3.44	3.65
19	2.90	3.46	3.55
20	2.70	3.22	3.64

Table 2. Mean values and standard deviations of the maximum temperature increase caused by Ar, CO_2 and N_2O with respect to air and measured by the sensor positioned on the bottom of the vessel.

	Ar	CO_2	N_2O
M.V. of ΔT	2.64	3.30	3.55
Std	0.19	0.21	0.20

The results obtained from the anemometer for a typical run are shown in figure 3.

It is evident even from a visual inspection of the figure that there are three zones of strong reduction in air speed. These zones exactly correspond to the initial intake of each new denser gas. In fact, no significant temperature reduction on the bottom of the vessel or at intermediate heights is visible in figure 2 at corresponding intake times (the time scale of figure 3 is shifted of about 6000 s with respect to figure 2); therefore, this speed reduction is not driven by temperature differences, which are eliminated by the thermalization step.

As one can see from the supplementary video, the air movement is once again strongly reduced or disappears when the new denser gas enters the box and the sensitive silk threads accurately reproduce this phenomenon.

An even wider and more accurate analysis of the convection phenomenon is shown by the results obtained using a set of eight thermometers placed at different heights along a wall of the box; the time evolution of the temperature values for the case of nitrous oxide intake is shown in figure 4.

Figure 4 shows the behaviour of the temperature in the box at different heights of a sidewall immediately before and after the input of nitrous oxide; at lower heights, below 9 cm, convection is always present, as shown by the negative trend of temperature versus height,

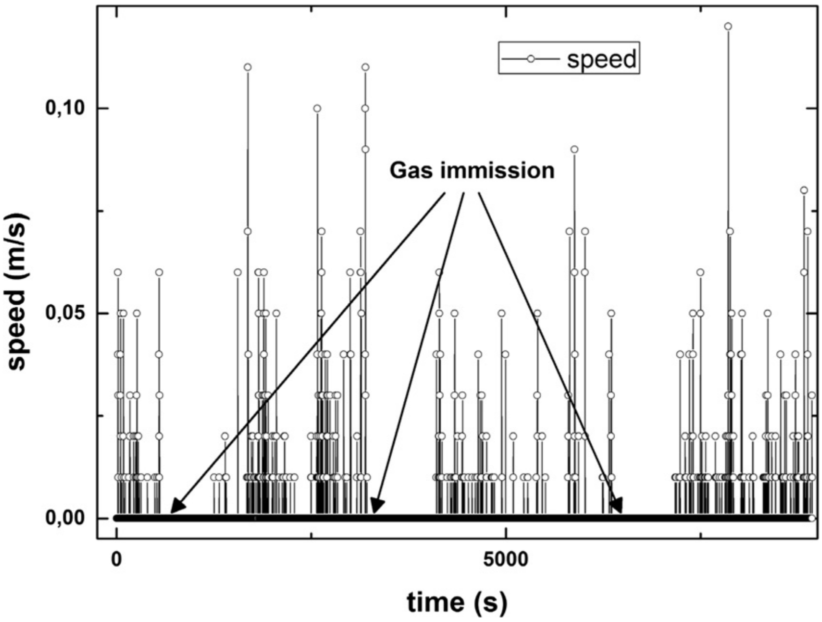


Figure 3. The velocity of gas at the top boundary of the Nalgene vessel shows three sharp reductions in correspondence with the three gases input.

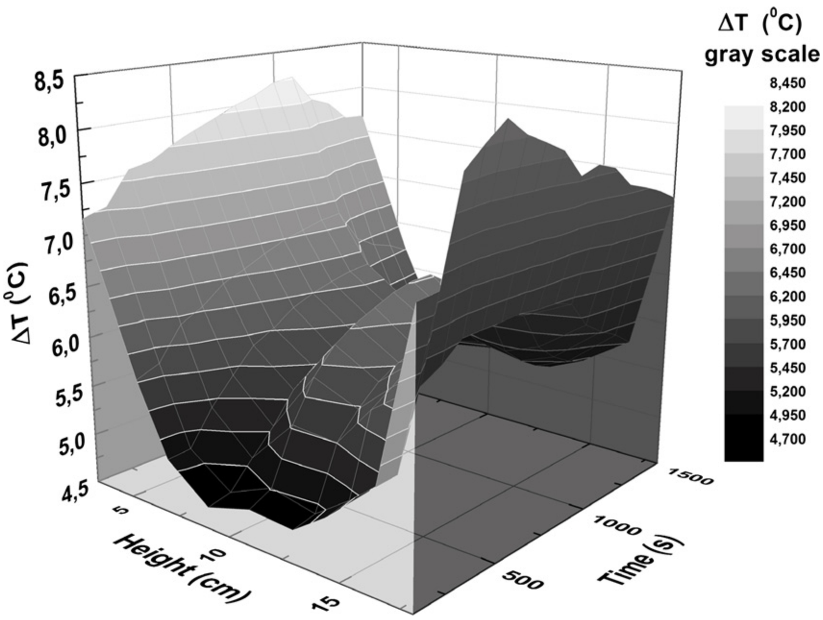


Figure 4. Different temperatures in the vertical zones of the box; the lowest zone, from 0 to 9 cm always shows the presence of a density inversion which is the basic condition for the presence of convection; above 9 cm the situation is different and varies with time as explained in the text (false colour scale for temperature).

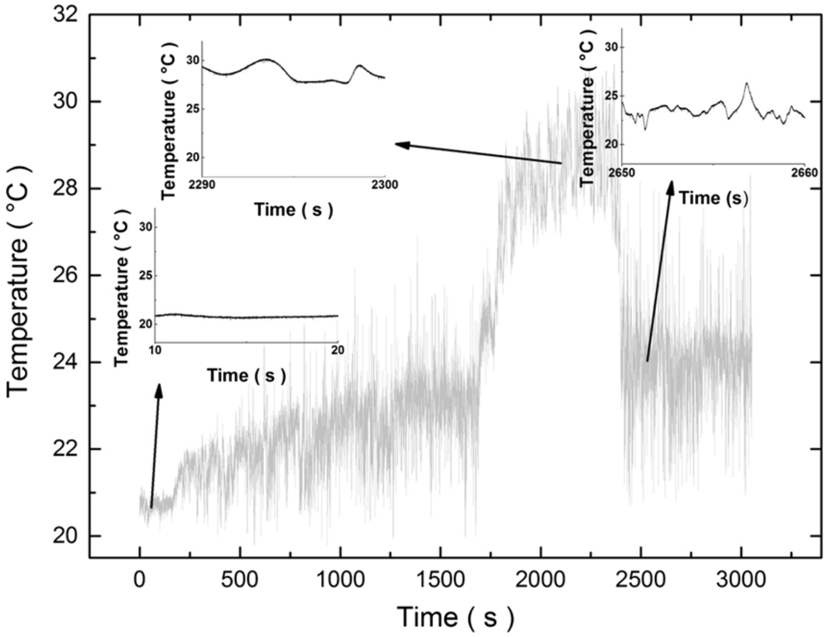


Figure 5. The temperature at the bottom as shown by the fast K-sensor at the beginning of the light-on step; the oscillation of the temperature is greatly enhanced, showing the presence of convection movements. In the three reduced scale graphs, the enhancement of the time scale and reduction of the temperature scale shows the difference more clearly: in the dark phase of the experiment the temperature is substantially constant, while slow oscillations are always present in the light-on step.

while above 9 cm the density trend is marginally stable and becomes very stable (positive trend of temperature versus height) during the intake of the new gas; only after a certain time does the system recede toward the initial state. At heights above 13 cm the density trend is always stable in all of the stages of the experiment (positive trend), so the 'driving force' of the gas movement is in the lower zone and the flow of the gas may be justified (1) by the general volume expansion of the gas in the box due to the temperature increase and (2) by the convection present in the zone of negative temperature versus height trend.

From an analysis of the literature for the so-called open shallow square cavity, there are three possibilities for the structure of convective motions: a torus, a roll and two rolls one on top of the other; the data of figure 4 seem to indicate that the latter structure could be the case for our experimental simulation. However, this point should be analysed better and eventually confirmed.

A final consideration on the experiments comes from the detailed analysis of the situation in the lowest zone, where the convection is essentially always present, performed using a fast thermocouple and shown in figure 5.

The comparison between the oscillation of temperature evaluated with this sensor at a height of 1 cm, before and immediately after the lamp is turned off, shows the beginning of strong local fluctuations in temperature, which indicates the existence of a constant local convection movement in the lower portion of the box: 'bubbles' of warmer gas continuously start moving up from the bottom of the box toward the higher and colder zone, above 9 cm. The bubbling mechanism probably depends on the role of gas viscosity, which delays the start of each bubble until a certain critical volume is attained.

The existence of this phenomenon and the negative temperature versus height trend above 9 cm reveal a possible weak point of the experimental apparatus of [1]; in fact, in the Wagoner *et al* apparatus, the bottom sensor is only adjacent to the bottom at an height of about 1 cm, as shown in figure 1 of [1], thus the temperature considered is not the effective bottom temperature, but is certainly lower due to the presence of temperature inversion and to convection 'bubbling'.

The application of the simple linear model of heat transfer used in [1] is certainly useful. However, some important points should be addressed: the first is the exact definition and the second is the numerical value of the coefficient f used in [1] for estimating of the radiative absorption of gases. The definition of f used in [1] is the a-dimensional isothermal ratio of the integral of a blackbody emittance function limited to the wavelength where the gas spectrum may be considered as 'saturated' with respect to the total integral of blackbody emittance. To this aim, the authors chose a limited wavelength interval for carbon dioxide, obtaining a final value of $f = 0.1$.

However the exact value of f may be defined as the 'normal total emittance', as defined in the literature [10, 11]. In the typical experimental setup, the carbon dioxide or nitrous oxide are at 1 bar pressure and have an optical path of 20 cm, this certainly allows the saturation for many of the absorption bands for a wavelength interval larger than the one chosen by [1].

Estimating f is of paramount importance in heat transfer studies and its value may be found in the literature. It is possible to use the most common value for carbon dioxide total emittance, calculated by Hottel *et al* in [12], which is commonly used even in teaching applications and which can be found in many textbooks [12]; for the conditions of our experiment the value is at least 0.16, significantly higher than the value used in [1]. For nitrous oxide it is possible to use the value calculated by Kunitomo *et al* in figure 8 of [13], about 0.25. The consequence is a significant increase of the role of gas radiative absorption and the expectation of a greater importance of absorption for nitrous oxide with respect to carbon dioxide.

There is a further significant point: in a general thermodynamic analysis of the system, one should also consider the direct absorption of the lamp's infrared radiation by gases as not due to the greenhouse effect, because there is an important component of infrared in the spectrum of the lamp used, which is not the case for the spectrum of the Sun through the Earth's atmosphere. Only a limited portion of the power of the Sun's spectrum is in the infrared interval, and the greatest portion of it is below 4 μm, so its warming role is limited. In our experiment, on the contrary, the direct infrared absorption of the infrared emitter 'lamp glass' by the gas is significant with respect to that from the vessel bottom.

The temperature difference of 0.25 °C found between carbon dioxide and nitrous oxide correlates only with the difference of their f coefficients, 0.09, (not with the absolute value of infrared absorption) and gives an idea of the importance of the radiative greenhouse effect and more generally of radiative absorption mechanisms.

Convection is certainly extremely important in the typical experimental conditions of the 'greenhouse in a shoebox' as indicated by [1], but the radiative effect may also be precisely detected using an appropriate strategy while maintaining the classic experimental design.

5. Conclusions

The results may be summarized as follows.

- In the typical experiment to reproduce the greenhouse effect in a box illuminated from above, the variation in the density of the gas used makes it possible to have a significant contribution to the reduction or even to the blocking of the convection and thus to the increase of the bottom temperature even with argon, a gas which cannot show a 'true' radiative greenhouse effect; this confirms the main conclusion of [1], that convection is a very important phenomenon in the 'greenhouse in a shoebox' experimental design.

- Using different gases such as carbon dioxide and nitrous oxide which have very similar densities, in both cases higher than air, and a strong radiative greenhouse effect the two mechanisms sum up. By comparing their results, it is possible to conclude that the maximum attained temperature difference (between the two gases which have the same density and so the same blocking effect on the convection) is due only to their different radiative greenhouse effects (and more generally to their different absorption spectrum), an effect which is stronger for nitrous oxide as may be calculated from its infrared spectrum. The significant difference of the maximum temperatures obtained with carbon dioxide and nitrous oxide disagrees with the claim of [1] that these kind of experiments are not useful in proving the greenhouse effect.
- The convection structure in the vessel is quite complex and from the data it appears that two rolls, one on top of the other, maybe the case for our experimental design; this point should be addressed better in the future. Numerical modelling could also be useful to overcome the limits of the steady state analysis.

Acknowledgments

We are grateful to A Zecca and S Siboni for helpful discussions and to M Grott, M Dimauro and D Avi for their skilful technical support. This paper is based on the final Master's thesis for the physics degree of MB, tutors: CDV and LMG.

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