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VOLUME HEATING OF A VERTICAL AIR COLUMN BY MICROWAVE RADIATION IN THE ATMOSPHERIC ABSORPTION LINE

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We propose a method of volume heating of a vertical air column by the vertically directed microwave radiation at the frequency of the spectral atmospheric-absorption line. The heating efficiency is estimated for the case of the molecular-oxygen absorption band near a frequency of 60 GHz. The proposed heating method can lead to the formation of new convection structures in an air column. Absence of natural ascending airflows with stationary heating over the entire flow length is noted.

1. INTRODUCTION

The experiments on the artificial action on the atmosphere (leading to formation of clouds, atmospheric vortices, etc.) by heating the air near the Earth surface using solar radiation or fuel combustion are well known [1–7]. The local character of heating near the Earth's surface when the temperature of the created air flow decreases with increasing altitude because of both natural cooling (about 1°C per 100 m of the altitude), which is related to expansion, and turbulent entrainment of the surrounding air into the flow, is a common feature of such experiments. The layer of atmospheric temperature inversion, in which the air temperature increases with increasing altitude and, therefore, its density decreases, is known to be an obstacle to ascending convective flows. The heated-air flow ascending under the action of the Archimedes force does not receive additional heat during the ascent and the remaining heat can be insufficient for "preserving the buoyancy" and overcoming the atmospheric inversion layer. Therefore, according to numerous observations, the vertical smoke columns in quiet atmosphere abut one smoke cloud under the inversion layer[1] and in some cases the flow stops even if the heat-source power near the Earth varies from 300 to 600 MW [5].

2. A NEW HEATING METHOD

In this work, we propose a new method for heating a vertical air column under the conditions of a quiet windless atmosphere to form an ascending flow. The estimates given below show that using the proposed method, one can create an ascending flow which is capable of overcoming the atmospheric inversion layers. This method involves the vertical air-column heating at each height point by the vertically directed weakly-divergent microwave radiation, which is tuned by frequency to one of the atmospheric absorption lines. In the microwave range, the absorption lines are observed in the atmospheric oxygen and water molecules (see, e.g., [8]). The atmospheric-line parameters are well known and their precise values and modern methods

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[1] Comprehensive demonstrative photo and video materials can be found in the Internet using key words or obtained from the authors of this work by request.

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for simulating the atmospheric-absorption spectra are, e.g., given in monograph [9]. During the molecule collisions, the microwave-radiation energy, which is absorbed by the molecules and distributed over their internal degrees of freedom, is converted to the energy of their translational motion, i.e., heat. Usually, one collision is sufficient for thermalizing the molecule, which absorbed a microwave-radiation quantum [8].

The new heating method will also presumably lead to new convective structures. According to the classical book [10], the flows, in which the density difference due to the thermal expansion is the only cause of the medium motion, are called natural convective flows. Natural flows, which emerge in the space that is not limited by the walls, are called free convective flows. A convective flow along the heated vertical wall, a natural convective flow from a heated round horizontal cylinder, a convective flow above a horizontal plate, mountain and valley winds in stratified air, etc. are referred to as the above-mentioned flows. Hundreds of works deal with each of these convection types. According to the terminology used in [10], convection, which appears during the proposed heating method, can approximately be classified as free convection in an atmospheric-air column heated over the entire volume. No ascending flows with volume heating over their entire extension are known to exist in nature and we believe that such a flow can be rightfully specified as a new convection type. Although the ascending convective air flows can be heated by heat release during the water-vapor condensation, this occurs only above the condensation point below which at least one atmospheric inversion layer is usually located.

3. PHYSICAL BASIS AND ESTIMATION OF THE METHOD APPLICABILITY

The intensity I of the vertically directed monochromatic radiation in a medium with the uniform absorption coefficient α decreases (without allowance for the beam divergence which is considered below) with increasing altitude h as

$$I = I_0 \exp(-\alpha h), \tag{1}$$

where I_0 is the source-radiation intensity near the Earth surface. In this case, the characteristic height of the heating decrease by a factor of $e = \exp(1) \approx 2.7$ equals $h_\alpha \approx 1/\alpha$. This allows one to choose the operation frequency, which corresponds to the line with a smaller or greater absorption coefficients depending on the heating purpose. In the millimeter and submillimeter wavelength ranges, there exist atmospheric-gas absorption lines, which can be either stronger or weaker than the well-known molecular-oxygen absorption line located near a frequency of 60 GHz [8, 9] and considered below as an example. To eliminate the influence of the local motions of the atmospheric parts with different temperatures and, thus, different densities and, in the general case, different complex refractive indices on the radiation propagation, it is convenient to choose the operation frequency of radiation at such a point of the dispersion curve of the medium at which the real part of the permittivity deviation from unity turns to zero. For the isolated spectral atmospheric line, this point corresponds to the absorption maximum. At this frequency, the real part of the refractive index of air is density independent and the local density variations do not lead to either deviation of the beam direction from the vertical one or additional divergence of the microwave radiation. Note that the Doppler shift of the molecular-absorption frequency, which is related to the air-flow motion, can be ignored mainly because the bandwidth of the spectrum region, in which absorption has its maximum and the real part of the refractive index is close to unity, is great (10^{-2}–10^{-3} relative units). It is determined by the intermolecular-collision frequency, which under the atmospheric conditions by 3–4 orders of magnitude exceeds the bandwidth (10^{-6} relative units) related to the thermal velocity of the molecule motion. In turn, the molecule-motion velocity by at least one order of magnitude exceeds the air-flow velocity.

Let us consider the absorption band of a magnetic fine structure of the rotational levels of molecular oxygen, which is located in the frequency range 50–70 GHz (the central wavelength is about 0.5 cm). In the band peak, the absorption coefficient ($\alpha_{\max}$) amounts to about $3 \cdot 10^{-5}$ cm^{-1} [9]. According to [11], for the oxygen band, the above-mentioned point of equality to zero of the real part of the difference of the refractive index from unity is located somewhat below 60 GHz. It should be noted that the air humidity, mist, dust, aerosols, and even snow or rain (except for tropical showers with intensity 50–100 mm/h) do not influence the existence and approximate location of this point. This is due to a small level of absorption (and refraction) by water vapors in this spectrum region [9, 11] and because the radiation wavelength is much greater than the characteristic sizes of the dust particles, drops, etc. It is exactly the small absorption level which stipulates usage of the millimeter-range waves for radar.

In the considered frequency range, there exist high-power sources of coherent radiation. Thus, as far back as 1984, "Varian" company announced creation of a continuous-wave (CW) source with a power of 200 kW at a frequency of 60 GHz [12, 13]. In 2017, the authors of [14] reported development of submegawatt CW generators operating in the range from 14 GHz to subterahertz frequencies. Modern achievements and the trends in the development of high-power gyrotron radiation sources are described in review [15].

Let us perform estimations using the CW power 600 kW (which has already been reached in [16]), the beam cross section 1 m^2, and the absorption coefficient $3 \cdot 10^{-5}$ cm^{-1}. In this case, 1800 W of radiation is absorbed on one running meter of the optical path, which leads to an air-temperature increase by about 1.5 deg/s for the heat capacity of one cubic meter of air about 300 cal/deg and the heat-outflow absence.

To understand sufficiency of such an energy contribution, let us show some rough estimates of heat losses for various environments. For the first estimate, we use the heat-transfer equation ignoring the turbulent diffusion across the air column. A heated vertical air column, with the Gaussian cross-sectional temperature distribution, the temperature difference 10°C between the center and the surrounding air, the cross-sectional area 1 m^2 over the half amplitude of the temperature difference is used as the initial condition. If it is assumed that cooling is only due to molecular diffusion (according to handbooks, the thermal diffusivity of air is about 0.2 cm^2/s [17]), the corresponding cooling at the column center occurs at a rate of 0.01 deg/s. The floating up of the heated air column leads to eddying (turbulent mixing) which is similar to the well-known vortices of the volumes of smoke rising from the chimneys (see footnote 1). In this regime, during the heat-exchange calculation, it seems to be reasonable to replace the coefficient of molecular thermal conductivity by the coefficient of turbulent thermal conductivity, which exceeds the molecular coefficient by 4–6 orders [18]. In this case, the heated-column cooling rate, which is directly proportional to the latter coefficient according to the equation of heat transfer, increases up to about 1 deg/ms. Irreality of the obtained result is proved by the fact that in this case one could not observe the rising smoke columns and the flow would immediately cool down near the chimney edge for several milliseconds. As a matter of fact, heat is carried upwards by the ascending flow rather than scatters in various directions. The fact that the smoke (or water vapor), which makes the shape and dimensions of the ascending flow visible, rises high in the sky in the quiet atmosphere, means that the turbulent heat exchange region is limited only by the flow region [18, 19]. Within the limits of this region, one can observe an intense heat exchange due to strong mixing, which is characteristic of turbulent motion and leads to a rapid temperature equalization at various parts of the ascending flow, while a vortex-free turbulent motion takes place outside the turbulent region to be gradually transformed to the laminar motion with increasing distance to the region boundaries [18, 19]. The cooling of the free convective flow is mainly governed by the surrounding-air entrainment into the rising flow. The entrainment velocity amounts to about 0.1 of the flow velocity [19, 20], i.e., is not high. This is exactly why the smoke columns can be high.

For the simplest empirical estimation of the average flow-cooling rate with allowance for the turbulent motion, it is assumed that the velocity of the smoke-volume ascent is independent of the altitude and amounts to about 1 m/s. The temperature difference between the smoke coming out of a factory chimney and the surrounding air is about 100°C. The smoke column in quiet atmosphere can be visually followed up to a height of about 100 m. In this case, it is assumed to cool down to the surrounding-air temperature. Therefore, the flow-cooling rate is on the average about 1 deg/s, which is smaller than the above-estimated rate of its heating by the vertically directed radiation with a power of 600 kW.

Let us estimate the heat loss of a free convective flow using another method. Let us use the results of calculating the parameters of the ascending flows heated near the Earth surface [10, 18–20], which show that the ascent velocity of a free convective flow varies as $h^{-1/3}$ with increasing height and the temperature decreases in proportion to $h^{-5/3}$. It should be noted that this is valid only for the formed flow and starting from the height that is much greater than the characteristic size of the flow source. We use the initial conditions, which are similar to those used above, i.e., the factory chimney has an output diameter of 1 m and the flow settles at a distance, which exceeds its diameter by a factor of e. Therefore, the flow velocity at a height of 100 m decreases to 25 cm/s and the difference between its temperature and that of the surrounding air amounts to 0.25°C. Thus, the flow can be assumed almost cooled, but still rising. The cooling rate is maximum at the lowest point of such a flow and amounts to about 60 deg/s for the chosen conditions. In this case, the cooling rate rapidly decreases with increasing altitude in proportion to $h^{-8/3}$ (since the rate is proportional to the temperature derivative) and amounts to only about 1.4 deg/s at a height of about 10 m from the chimney edge, i.e., becomes smaller than the microwave-heating rate and turns out to be equal to the cooling rate determined by molecular diffusion at a height of 50 m. Note that such a high-rate cooling of the flow, which was heated at the Earth surface and received no additional heating on the way, seems to be a reason that stop the flow supported by the source with a power of 600 MW at the Earth surface [5]. As is proposed in this work, the flow, whose heating is almost uniform at each air-column point with increasing altitude, is much more expedient. Unfortunately, theoretical calculations for estimating the heat loss are absent in this case. This issue will be considered below.

The well-known relationships for the ascent velocity and the temperature in a free natural convective flow can also be used for another estimation of the heat loss using the proposed heating method. Assume that microwave radiation is switched on in the quiet atmosphere. Let the initial laminar motion of the gradually heated air be preserved during the first second. This allows one to ensure an almost loss-free initial heating of the air column by 1.5°C compared with the surrounding air. Applying the above-mentioned relationships to the ascending flow, which is formed under such conditions, we see that the maximum rate of the air-column cooling is only 0.9 deg/s, i.e., lower than the heating rate.

Therefore, using the results obtained for convective flows of quite other types for estimating the heat loss, it can be shown that continuous supply of the microwave energy to the ascending flow is sufficient to also keep it buoyant in the atmospheric inversion layers. The atmospheric inversion varies from fractions of a degree to about 15° C–20° C according to [22] (which seems to cover all the situations which are possible on the Earth and can be encountered in the equatorial-desert regions and up to the cold poles) or, according to the experimental data [5], from the fractions of to several degrees. The heating of a vertical air column, which is required to overcome the inversion layer, is reached for about half a minute even under unfavorable experimental conditions when the temperature inversion amounts to 15° C–20° C.

At an altitude of 330 m (approximately equal to $1/\alpha_{\max}$), the heating decreases to 0.3 deg/s (17 deg/min) because of the diffraction divergence of the beam and power decrease because of the radiation absorption. The diffraction divergence of the beam amounts to λ/D, where λ is the wavelength, which is about 0.5 cm in the case under study, and $D = 1$ m is the radiator size. In the considered example, λ/D is about $5 \cdot 10^{-3}$ rad or 17 angular minutes. Note that in the millimeter-wave range, there exist radiators with diameter up to tens of meters, using which, one can focus radiation at a certain height within the limits of the diffraction length $d = D^2/\lambda$. This ensures a slower heating decrease with increasing height compared with that which follows from Eq. (1).

As it seems, the issues of the radiation-power sufficiency for various purposes should be addressed experimentally. It is quite possible that the pronounced effect of the air-column heating can also be observed for the radiation powers, which are significantly lower than that used for estimation exactly because of the continuous volume heating over the entire column length. It is also possible that a further increase in the radiation power (e.g., smog-dispersion experiments) is required for some practical purposes. In this respect, we should remind of the development of a 2 MW CW gyrotron [15] and multimegawatt CW sources in the range from tens to hundreds of gigahertz [14]. To heat the air, the radiation source can also be pulsed with sufficiently high mean power. In the above-mentioned work [16], a power of 1 MW was maintained for 800 s, while [15] reports on maintaining a power of 0.92 MW for 30 min.

Even for such high radiation powers, one should not expect the manifestation of the nonlinear spectroscopic effects, which are, in particular, related to saturation of the molecular transitions forming the atmospheric-oxygen band. This is attributed to the high rate of the collisional relaxation of molecules under atmospheric pressure (the half width of a single atmospheric oxygen line amounts to about 1.5 GHz, which corresponds to the relaxation time about 100 ps) and the smallness of the matrix elements of the dipole moments of the corresponding transitions. The matrix elements of the dipole moments of the fine structure of the oxygen molecule have a value of the order of Bohr magneton [12], which is equivalent to about 0.01 D. The power at which the line saturation starts is determined as [8, 21]

$$P_0 \sim h^2(\Delta\nu)^2 cS/(8\pi\mu_{ij}^2), \tag{2}$$

where h is the Planck constant, $\Delta\nu$ is the line halfwidth, c is the speed of light, and μ_{ij} is the matrix element of the dipole moment of the molecular transition between the energy levels i and j. For the considered conditions, saturation starts with the power fluxes exceeding $p_0 = P_0/S \approx 10^8$ W/cm^2 [23] which exceeds all the values mentioned in this work by several orders. For the considered example of a radiator with a power of 600 kW and a size of 1 m^2, the power flux equals only 60 W/cm^2.

The necessary requirements for the stability of the radiation-source frequency can be totally satisfied using the phased-lock loop (PLL) of the radiation frequency, which, as is shown in [24], can ensure the gyrotron-radiation spectrum width below 1 Hz. Note that such a high stability is excessive. Indeed the spectral-line width at the half amplitude in the near-surface atmospheric layer amounts to about 3 GHz for a single oxygen line and about 6 GHz for the water line [9]. The oxygen band in the neighborhood of a frequency of 60 GHz, which consists of several tens of single lines, whose contours fully overlap at atmospheric pressure, extends from about 50 to 70 GHz. As the height increases, e.g., to 20 km, the collisional width of the lines decreases only several times. Therefore, to maintain the source frequency within the required limits (e.g., near the above-mentioned point at which the real part of the refractive-index difference from unity is equal to zero), it is sufficient to have the usual parametric stability, which is simply ensured by the temperature and power-source stability. The radiation-frequency variations within several megahertz (see, e.g., Fig. 1 from [24]), which are possible in this regime, do not impact the heating results. An increase in the radiation power is simplified for the same reason by using many sources whose frequencies are within the required limits for a particular atmospheric line.

It is noteworthy that the proposed method can use many radiation sources without the requirement of mutual coherence of the radiation generated by them, i.e., without using the PLLs. Increasing the number of sources makes it possible to increase both the radiation-beam power and the cross section. In this case, it is possible to use the experience of the ITER project [25], which assumes simultaneous operation of 24 gyrotrons of megawatt power at a frequency of 170 GHz. In the case under study, different sources can be tuned to the frequencies of different atmospheric spectral lines, which have different absorption coefficients, for optimizing the heat distribution over the altitude.

In the general case, estimation of the shape and the parameters of motion of the air flow created by the volume heating of the air column seems to be difficult. The modern state of calculations in this field is reflected in, e.g., [19, 20, 26]. These works, among other issues, deal with analysis of the dynamics of convective ascent of the spatially localized ascending flows in the atmosphere. Let us note that the flow updraft in these works, as in our case, is considered for the quiet atmosphere without allowance for the influence of wind and horizontal drift of the heated flow. The behavior of the ascending plume, which is considered in [19, 20], shows that even in the usual case of a turbulent flow heated at the Earth surface, the divergence angle of the vertical flow and the velocity of the surrounding-air entrainment into the flow have to be taken from the experimental data. In this respect, let us quote the lectures [20]: "No one has yet proposed theories that predict the numerical values of the angles relating size to distance, the ratio of entrainment velocity to mean velocity." In the considered case, if the heating is used at each flow point, the calculation becomes more complicated and experimental data are not available.

4. CONCLUSIONS

Hopefully, the character of the vertical flows in the quiet atmosphere remains unchanged up to a certain radiation-power level. This is supported by identical divergence patterns of convective flows from a village stove and a factory chimney (see footnote 1). In this work, we have considered a rather frequent case of the quiet atmosphere, i.e., the conditions under which smog can be observed. The flow-character preservation is indicative of the possibility of "rendering help" to the chimney flows in overcoming the atmospheric inversion layer using the above-described method in the case of comparatively low radiation powers.

For high levels of the radiation power, the flow character can be changed. The new heating method is also assumed to result in new convective structures at each air-column point, which still have to be calculated and simulated. Another circumstance, which complicates the calculation is related to the experimental fact of the ascending-flow swirling (see footnote 1). In many cases, the flow swirling is invisible and can only be observed owing to the flame tails, as has been shown in the above-presented examples, or artificially added smoke (e.g., see presentation of the greatest hand-made tornado at the Mercedes-Benz museum in Stuttgart, Germany, footnote 1). The ascending-flow instability to the swirling has been noted in some calculations and experiments [2, 4, 27–29]. As far as we know, the problem of convection for a flow heated over its entire length has not yet been solved.

Therefore, comprehensive calculation of the flow shape and motion parameters is absent even for a simpler case of the surface heating. In the case of heating at each point of the vertical air column, the swirling instability seems to be even more pronounced. The general pattern of the ascending flow is preserved in the sense that a warm-air column on the whole floats up in a colder surrounding atmosphere. Recall that floating occurs mainly along the heated region with a small transverse expansion. In this case, cold air immediately above the floating flow is absent in the stationary regime. This allows us to assume that the flow is centered by the optical axis of the beam, which still increases its floating velocity. In [18], Landau derived the proportionality of the ascending-flow radius to its ascent height in the case of heating from the Earth surface just on the assumption of dimensionality in the absence of other characteristic dimensions. In the case of heating by microwave radiation, another dimension, i.e., the microwave-beam diameter, appears in addition to the height. The relationship between these quantities is unknown and is waiting for theoretical consideration. For example, it is of interest to study the experimental dependence of divergence of the convective air flow with increasing height on the heating power and the microwave-beam divergence angle. To specify the details of this motion, further theoretical and experimental studies, which are beyond the scope of this work, are required.

The possibility of heating an air column at each point over the entire height of the column at a rate reaching several degrees per second, which was shown above, is new for the atmospheric studies. We do not know about either theoretical or the corresponding experimental studies which consider such a possibility. In our opinion, such studies are of keen interest for both atmospheric physics and, probably, practical applications. Since the ascending air flows heated over the entire extension of the flow are not known in nature, the experiments can demonstrate new forms of convective motion in the atmosphere which were not previously observed.

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