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Experimental study of thermal convection in dry air by holographic interferometry method

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Abstract. The convection of humid and dry air was studied experimentally. The observed fluid convection involves two mechanisms of heat and mass transfer: thermal convection produced by temperature gradient and concentration convection occurred due to the inhomogeneous vapor distributions induced by evaporation and condensation of water. The convection stability of humid air was described in terms of two (thermal and concentration) Rayleigh numbers. Laboratory experiments were performed using holographic interferometry and thermocouple techniques. Experimental holograms were processed numerically in order to calculate the space distribution of the refractive index in relation to temperature and vapor concentration. The results show that the difference between moist convection and dry convection can be measured even in the absence of evaporation and condensation. The experimental interferograms for dry air (intentionally dried up to 4 % relative humidity) are given. The justification of this research requires an additional quantitative comparison with the measurements obtained for humid air (with 100 % relative humidity) undergoing the first-order phase transition of the “gas-liquid” type.

1. Introduction

Heat transfer by convection occurs as a result of the macroscopic movement of fluid that remains in motion until equilibrium is reached. Convection plays a key role in all dynamic processes observed in nature and takes place in a great variety of technical applications, among which those associated with humid air are of our main interest. The flows of air in the Earth's atmosphere require a physical and mathematical description in terms of gas dynamic models. The study of convection in the atmosphere is of great significance for developing new weather and climate forecasting methods. There are numerous papers (e.g. [1-5]), in which special attention is given to investigating the relationship between different types of atmospheric circulation and weather changes. The important role in the convection of humid air is played by the first-order phase transition in the “water – vapor” system [6], but only the latent heat of phase transition is usually taken into account, because the dimensionless thermal Rayleigh numbers calculated for humid and dry air are very close. However, along with the thermodynamic processes of heat absorption (during evaporation) and heat emission (during condensation), the intensity of the convection flows of humid air is influenced by local changes in pressure and specific volume of water vapor. The evaporation of water in one area and the



condensation of water vapor in another area can significantly change the convective flow, but there is almost no experimental data highlighting the difference in convection between dry and humid air in the presence of the first-order phase transition of the "gas-liquid" type. The purpose of this study is to investigate experimentally the difference between thermal convection in dry air and thermosolutal convection in humid air subject to the first-order phase transition under conditions close to those observed in the atmosphere within the temperature range from 0 C to 60 C. In fact, the present study is preliminary, because it involves only one part of the work (concerning dry air); the results of our experiments with humid air which are currently performed would justify its scientific importance.

2. Dimensionless parameters

The studied problem focuses on the changes in temperature and concentration that occur in a mixture of two gases: dry air and water vapor. The thermal Ra_T and concentration Ra_C dimensionless Rayleigh numbers are used to take into account both mechanisms observed experimentally. The effective Rayleigh number Ra_E is the sum of both mechanisms

$$Ra_T = \frac{\varepsilon C_p \rho^2}{\kappa \eta} \cdot \frac{d^3 \Delta T}{T_0}, Ra_C = \frac{\varepsilon}{\eta D} \cdot d^3 \Delta \rho_c, Ra_E = Ra_T + Ra_C, \quad (1)$$

where d is the characteristic size of the cavity with moist air, ΔT is the temperature difference, T_0 is the average temperature in the cavity, κ is the thermal conductivity, C_p is the specific heat of the gas mixture, η is the dynamic viscosity, D is the kinematic diffusion coefficient for the gas mixture, ρ is the average gas density, $\Delta \rho_c$ is the change in density caused by the change in the concentration composition of the gas mixture.

The results (1) obtained using the semi-empirical equations from the paper [7] illustrate the dependence of the parameters C_p , κ , η , D , ρ on the pressure, temperature and composition of the "dry air - water vapor" mixture. Besides, the average temperature T_0 , optimal experimental cell size d and temperature difference ΔT which could produce convection are calculated. According to the paper [8], the process of convection occurs when the effective Rayleigh number Ra_E exceeds the critical Rayleigh number $Ra^* = 1700 \pm 50$.

For the experiments with dry and humid air, a holographic interferometry technique was chosen. We used this method to visualize the distribution of thermal and concentration fields in transparent media that fill a container (a measuring cell). A significant advantage of the holographic interferometry method, apart from its high sensitivity and accuracy, is that it does not require long coherence length of the laser beam and is not sensitive to the quality of optical components; so there is no need in the expensive interferometric plane-parallel glasses and mirrors.

3. Experimental setup

The schematic diagram of the experimental setup is shown in **Figure 1**. The central part of the setup is the sealed measuring cell 15x15x320 mm filled with the investigated fluid – dry or humid air.

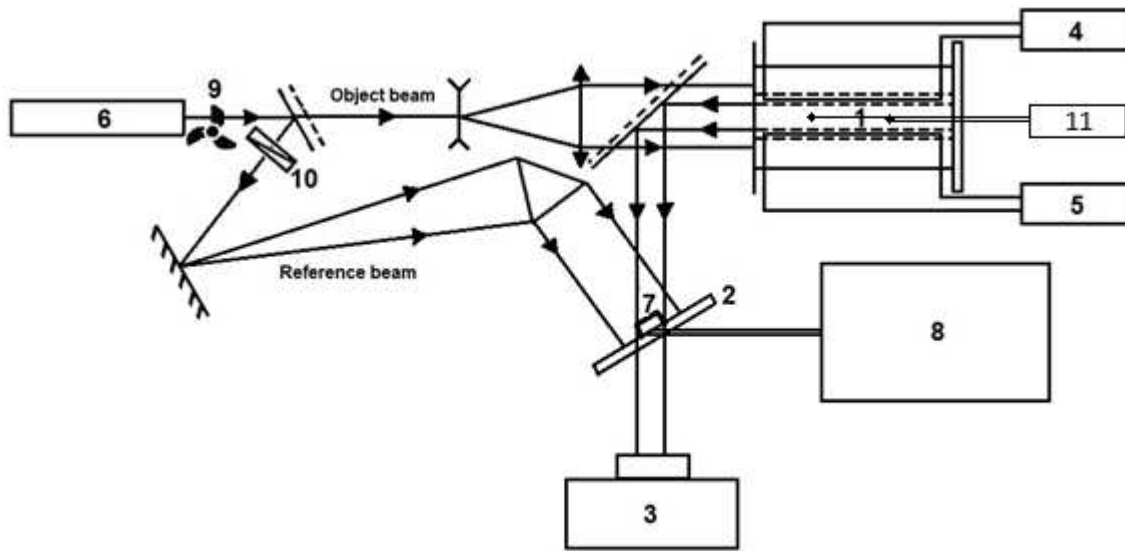


Figure 1. Scheme of the experimental setup: 1 - measuring cell filled with dry or humid air; 2 - holographic glass plate; 3 - video camera; 4, 5 - heat exchanger and thermostat of the cooler and heater, respectively; 6 - HeNe laser; 7 – photodiode (removable); 8 - Unipan selective nanovoltmeter type 237; 9 - obturator; 10 - polarizer; 11 – analog-to-digital converter LAI24USB measuring temperature in the cell with four differential thermocouples.

All the elements (**Figure 1**) were mounted on the holographic table with four inflatable structures applied to minimize the external mechanical vibrations affecting the setup during the hologram shooting process. The intensities of the reference and object beams were equalized to reach a good contrast. The equalization was achieved by attenuation of the reference beam with the help of a polarizer. No additional analyzer was required because the initial laser beam was precisely polarized with a polarization ratio of 500:1.

In the present study, convective flows have been also recorded by the standard thermocouple method. For this purpose, we used four differential manganine-constantan-manganine thermocouples, which were placed along the vertical walls inside the measuring cell at a distance of 15 cm between each pair of junctions, and at the distance of 4 mm (which exceeded the boundary layer) towards the center of the cell. The thermocouples were held in place with the pins made of thermal insulation material and connected to the external 24-bit analog-to-digital converter used to measure the signal (thermo-EMF) from each differential thermocouple.

To dry the air inside the measuring cell, an auxiliary dehumidifying setup was assembled (not shown in **Figure 1**), which included a closed container filled with silica gel, a low-performance (15 l/min) electric pump and connecting hoses. The auxiliary setup prepared the air by circulating it in the “experimental cell - silica gel container” closed contour for several hours before interferometric measurements of convective flows. The relative humidity of the dried air was controlled with a DHT-22 sensor. The dehumidification process typically lasted for several hours. The resultant value of relative humidity inside the experimental cell varied in the range of 4-7 % while the relative humidity of ambient air exceeded 50 %.

4. Results

The observations of convective flows in the air without its preliminary drying or humidifying were made for test purposes. The interferograms for the room air with approx. 50 % relative humidity are shown in **Figure 2**.

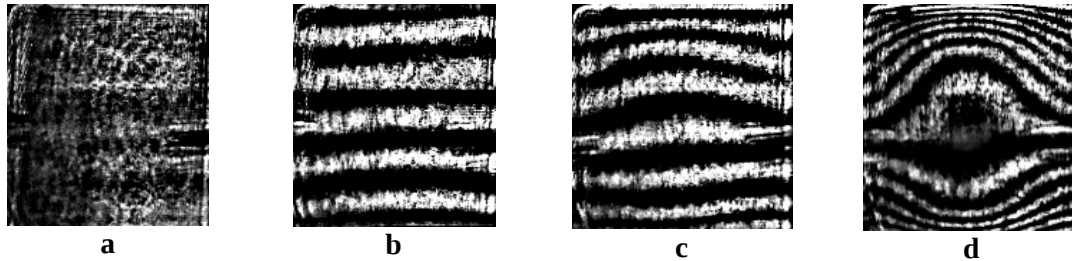


Figure 2. Experimental interferograms: a) isothermal air, b) vertical temperature gradient (cold top and hot bottom), c) small vertical T gradient producing moderate convection (hot bottom and cold top), d) big vertical T gradient (intensive convection)

As we can see, the interferogram at zero temperature gradient does not contain any interference bands (**Figure 2.a**). An increase in the heater temperature (bottom plate) leads to the appearance of an interferogram (**Figure 2.b**) which demonstrates parallel interference bands that correspond to temperature isolines (an equal thickness of the bands indicates that the temperature gradient is constant along the cell height). Further temperature increase leads to the bending of interferometric bands (**Figure 2.c** and **2.d**), which is the indication of the presence of intensive convective flows in the cell. These test results clearly demonstrate air convection flows can be investigated, both qualitatively and quantitatively, by means of the holographic interferometry method.

The next step was to study air convection in the absence of water vapor. For this, we performed a series of test experiments in the following temperature range: $T_0 = 15$ to 60 C with a step of 1 C and with a temperature difference of $\Delta T = 0$ to 20 C. A few interferograms for the dry air (4 % relative humidity) are shown in **Figure 3**.

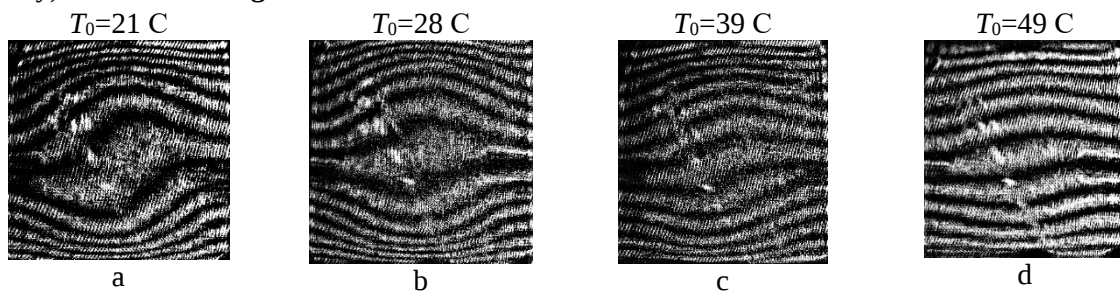


Figure 3. Interferograms for the convective flows of dry air at varying average temperature T_0 but for the same temperature difference $\Delta T=20$ C

The last figure is for demonstration purposes only, however it is interesting to note the sensitivity of interferometric measurements: interferograms clearly show that the intensity of convective flows depends significantly on the average temperature. The increase of T_0 causes the decrease of the convective flow intensity. This behavior is explained by the decrease of the thermal Rayleigh number Ra_T due to the increase of gas viscosity η with temperature T .

We measured temperature during the experiment with the help of differential thermocouples. If there was no convection in the cell, the signal was 0 V. At the moment when a convective single flow appeared, the threshold signal from thermocouples was registered (**Figure 3**). The application of these two (interferometry and thermocouple) methods made it possible to detect and observe convection in the measuring cell.

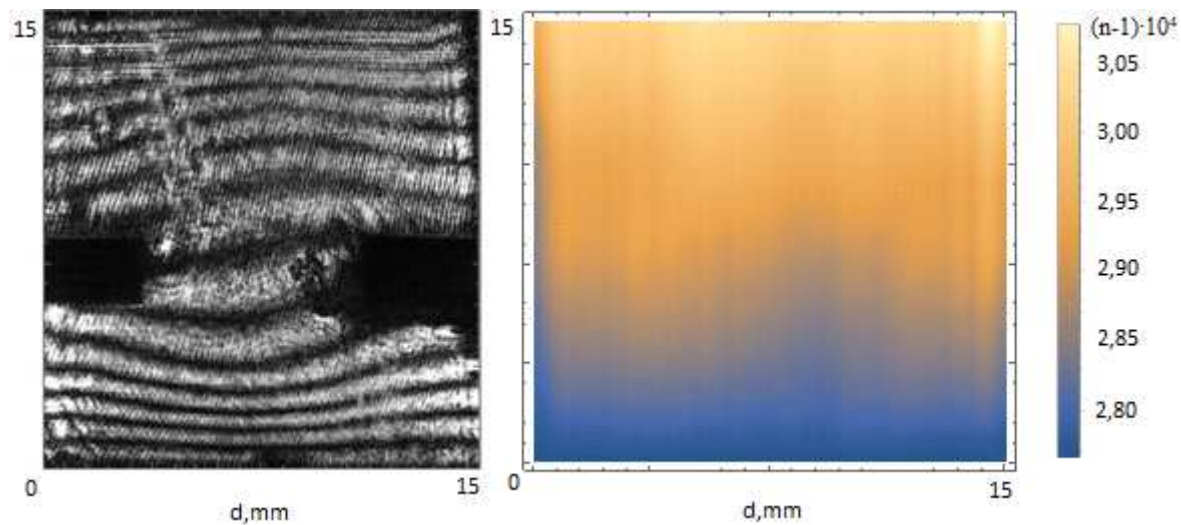


Figure 4. Program analysis (right) of the experimental interferogram (left): the spatial distribution of the refractive index $n(x,y)$ restored according to [9]

For each pair of $(T_0, \Delta T)$, the refractive index fields $n(x,y)$ were restored analyzing the experimental interferograms. The restoration procedure implied numerical processing of interferograms in accordance with the intensity distribution in the original digital images, which were processed using the Mathematica 12 computer algebra system. The example of the resultant numerical processing is shown in **Figure 4**. It is seen that the refractive index grows vertically according to the temperature gradient. At the same time, the temperature field distortion caused by the counterclockwise convection flow leads to a local decrease of $n(x,y)$ on the right side of the container. This stands for the rise flow of the hot gas along the right wall of the container. On the left side of the image, the refractive index values are higher than on the left side, because the cold gas flows down along the left wall. Hence, it follows that the use of both experimental and numerical methods allows visualizing and analyzing the convective structures.

5. Conclusion

The convection of humid and dry air has been studied experimentally. For this purpose, a series of laboratory tests has been performed using holographic interferometry and thermocouple techniques. The experimental holograms were processed numerically in order to determine how the space distribution of refractive index varies with temperature and vapor concentration. For interferogram processing, the software approach was implemented: the program code for the system of computer algebra Wolfram Mathematica 12 was written. This made it possible to analyze the interferograms obtained and to calculate a refractive index for further quantitative analysis. The experimental results showed that the difference between moist convection and dry convection can be measured even in the absence of evaporation and condensation. Experimental interferograms for dry air (dried up to 4 % relative humidity) are given. The research presented here is a preliminary study; the justification of its scientific relevance requires an additional quantitative comparison with the measurements obtained for humid air (with 100 % relative humidity) subject to the first-order phase transition of the “gas-liquid” type.

References

1. Chandrasekhar S 1961 Hydrodynamic and Hydromagnetic Stability (Clarendon Press: Oxford, UK)

2. Martynenko O G and Khramtsov P P 2005 *Free-Convective Heat Transfer* (Springer: Berlin, Germany)
3. Ogura Y A 1963 Review of numerical modeling research on small-scale convection in the atmosphere *Meteorological Monographs* 65–76
4. Arakawa A and Jung J H 2011 Multiscale modeling of the moist-convective atmosphere *Atmospheric Research* **102** 263–285
5. Derbyshire S H, Beau I et al. 2004 Sensitivity of moist convection to environmental humidity *Quarterly Journal of the Royal Meteorological Society* **130** 3055–3079
6. Shmerlin B Y and Kalashnik M V 2013 Rayleigh convective instability in the presence of phase transitions of water vapor *Physics-Uspekhi* **56** 473–485
7. Somov S A and Ivanov A S 2019 Experimental Setup for Studying Thermosolutal Convection in Moist Air *IOP Conference Series: Materials Science and Engineering* DOI:10.1088/1757-899X/581/1/012016
8. Gershuni G and Zhukhovitsky E 1972 *Convective stability of an incompressible liquid*
9. Hauf W, Grigul U 1973 *Optical methods in heat transfer*