Experimental Study of Dehumidified Air Convection by Holographic and Thermocouple Methods

S A Somov* and A S Ivanov

Institute of Continuous Media Mechanics Ural Branch of Russian Academy of Sciences the affiliate of Perm Federal Scientific Research Center, 1 Korolev str., Perm, 614000, Russia;

E-mail: *somov.s@icmm.ru

Abstract. Thermal convection of dehumidified air is studied experimentally under conditions close to normal (atmospheric pressure \( \approx 740 \) mm Hg, temperature range \( T = 0 \ldots 50 \) C). The study is based on fundamental experiment, which is focused on the physical aspects of thermoconcentration convection in fluids, undergoing first-order phase transitions of the “gas-liquid” type. The peculiar features of convection, caused by concentration changes of water vapor (as a result of its evaporation or condensation), are discussed in terms of dimensionless parameters. The couple of standard complementary experimental methods are used: holographic interferometry for visualization of convective flows and thermocouple method for heat flux measurements. Test experiments demonstrate and approve the design characteristics of the setup. The observations of convective flows in dehumidified air are demonstrated. Experimental setup is described in all details, including the original design of the cold heat exchanger (resembling a heat tube), proposed for next experiments with humid air.

1. Introduction

There is currently a lack of reliable experimental studies of convection in fluids, undergoing first-order phase transitions of the “liquid – gas” and “gas – liquid” types. This problem is essential for understanding chemical processes in reactors, natural circulation of air in the Earth’s atmosphere [1-5]. The reasonable motivation for laboratory experiments is the need to understand and verify analytical models, capable of describing and predicting these processes for the needs of chemical industry, weather forecasts, etc.

Earlier we presented numerical estimations of dimensionless thermal Rayleigh numbers \( Ra_T \) for humid and dry air [6], calculated for the following conditions: standard atmospheric pressure (760 mm Hg) and the temperature range \( T = 0 \ldots 50 \) C. It was shown, that the difference between \( Ra(T) \) curves for humid and dry air does not exceed the typical inaccuracy of experimental measurements (5 %). As far as there is no significant difference, one can perform all calculations using the data for dry air without taking its humidity into account. However, this approach is valid only when there is no “water-vapor” phase transition. Of course, it is insufficient to study heat and mass transfer in humid air, using the model of thermal convection with elements of thermodynamics (e.g. [7]). This approach takes into account only the caloric effects, associated with the release or absorption of the latent heat, but ignores all the rest effects (excluded volume, pressure variation, etc.). We suggest to study this problem in the framework of thermoconcentration convection, since heating or cooling of the fluid causes evaporation or condensation of vapor, what changes the concentration composition of the gas.

The proposed approach implies experimental investigation and comparison between thermal convection in dry air on the one hand, and thermoconcentration convection in humid air on the other hand. The present work describes the physical grounds of the problem, experimental technique and
laboratory measurements performed for the case of dehumidified air. We also discuss some modifications of the setup, which make it possible to perform convective experiments with fluids, undergoing first-order phase transition.

2. Experimental setup
To study convective heat and mass transfer in the air we have chosen the couple of standard complementary methods: holographic interferometry [8] for visualization of convective flows and thermocouple method for heat flux measurements. The first method allows one to visualize the real time distribution of thermal and concentration fields in light-transparent objects. A significant advantage of the holographic interferometry technique is that it is relatively undemanding to the coherence length of the laser light, and to the quality of the optical components (lenses, mirrors) either. There is also no need in interference parallel glass plates – the most expensive components of other interferometry techniques [8]. The standard thermocouple method is used to determine the beginning of convection, to calculate the heat flux and Nu number. In the absence of convection $\Delta T = 0$, because the temperature gradient is the same along both vertical walls. When convection starts, the temperature along the walls becomes different, the differential thermocouple signal becomes non-zero and proportional to the convective flow intensity.

![Figure 1. Measuring cell (front view): 1 – rectangular convective cell 15x15x320 mm with thermocouples, 2 – heat exchangers, 3 – housing, 4 and 5 – four copper pipes per each heat exchanger connected to liquid thermostats](image)

![Figure 2. Main single flow (red streamlines) inside the rectangular convective cell allows to simplify the problem and analyze it in the framework of the 2D approach](image)

The experimental measuring cell (Fig. 1) consists of the hermetically sealed housing on legs made of carbon steel; two copper heat exchangers (cool top and hot bottom) are attached to the housing with the help of stainless steel threaded studs with heat insulating collars; two vertical textolite walls between the exchangers form the convective cell area 15x15x320 mm. Two pairs of differential manganin-constantan thermocouples are mounted along the $z$-axis in the central part of textolite walls on special heat insulating racks (small foam plastic cylinders 2 mm in diameter and 3 mm high) protruding into the center of the cell in order to eliminate the influence of the boundary layer near the wall. The significant segments of thermocouple wires (100 mm) are placed along the wall on purpose: the thermocouple wires are allocated along the temperature isolines (which are parallel to the wall) and thus it increases the accuracy of temperature measurements, because the thermocouple metal wire itself is a good heat conductor. Manganin wire is used instead of the more common copper wire for the same reason: the thermal electromotive force in couple with constantan is approximately the same for both
metals, but the coefficient of thermal conductivity differs significantly: 21.7 \text{ Wm}^{-1}\text{K}^{-1} and 400 \text{ Wm}^{-1}\text{K}^{-1} at \( T = 0 \) \( \text{C} \) for manganin and copper respectively \[9\].

**Figure 3.** Scheme of the experimental setup: 1 - measuring cell filled with dry or humid air; 2 - glass holographic photoplate; 3 - video camera; 4 - top (cold) heat exchanger and its thermostat; 5 - bottom (hot) heat exchanger and its thermostat; 6 - He-Ne laser; 7 - sensor; 8 - selective nanovoltmeter; 9 - obturator; 10 - polarizer; 11 - LA-i-24USB; 12 - moisture sensor DHT-22 with digital display operated by microcontroller; 13 - micro-flow electric pump; 14 - silica gel container

The convective cell shapes and forms the convective flow (Fig. 2), whose first convective mode corresponds to a convection roll with axis of symmetry parallel to the \( z \)-axis. This geometry allows us to study the problem experimentally in the framework of the two-dimensional (2D) approach.

The scheme of the experimental setup is shown in the Fig. 3. The source of coherent light is the He-Ne laser JDS Uniphase 1103P (wavelength 633 nm, polarization ratio 500:1). The laser beam is divided by means of a translucent mirror into the reference and subject beams. The reference beam reflects several times from the mirror system and falls on a glass holographic photoplate of high-resolution (>5000 lines per 1 mm), where it interferes with the subject beam, which passes twice through the convective measuring cell. The hologram image obtained on the glass photoplate is recorded by a video camera. All elements of the setup are mounted on the holographic table damped by four air cushions in order to minimize the harmful mechanical vibrations affecting the setup while the hologram is being shot.

Before the hologram is shot, the intensity of the reference and subject beams is equalized in order to increase the contrast of interference fringes. The equalization of light intensity was achieved by attenuation of the reference beam with the help of one polarizer (additional analyzer was not required, as far as the laser light is already polarized). The hologram is shot in a dark room, just a small backlight passing through the dark green filter \( N 170 \) is allowed. The holographic photoplate itself is rigidly fixed during the whole experiment: this is the only possible way to achieve high-contrast accurate images of interference fringes.

An auxiliary setup was assembled and attached to the sealed measuring cell (Fig. 3) in order to dehumidify moist room air for basic experiments with dry air. The auxiliary setup consists of a 5 liter tank filled with silica gel, a low-performance (15 l/min) electric air pump and silicone tubes connecting altogether into a closed sealed system. The pump circulates the air inside the loop consisting of the experimental cell and silica gel container. The resultant relative humidity of the dry air inside the cell is permanently measured and displayed by the Arduino microcontroller with the help of the DHT-22.
sensor. As a result, the value of relative humidity inside the experimental cell varied the range of 4-7% while the relative humidity of the ambient room air was typically 43-47%.

3. Results and discussion
A series of laboratory tests were performed with the help of experimental technique described in the previous section. Initial adjustments of the experimental setup were performed with the help of test observations of convection without preliminary drying or humidifying (Fig. 4). As one can see, the interference pattern does not contain interference fringes at zero temperature difference between the top and bottom heat exchangers. When heated from above, we can notice a stable temperature stratification without macroscopic fluid flows. When heated from below, the interferometric fringes begin to curve. The curvature of fringes clearly demonstrate how intensive the fluid convection is (Fig. 4 c, d). Thus, the experimental technique allows to visualize convective structures.

![Interferograms](image)

**Figure 4.** Interferograms for: a – isothermal air (no macroscopic flows); b – stable stratification caused by temperature gradient (heating from above); c – noticeable convective flow (heating from below); d – intensive convection (heating from below)

Other results are shown in the Figs. 5, 6 for demonstration purposes in the range of parameters $Ra = 0...2 \cdot 10^3$, $Pr = 0.74...0.84$, $Sc = 0.86...0.9$. The interferograms show that for the same temperature difference $\Delta T$ between the cooler (top) and the heater (bottom), the convective flow is attenuated with the increase of the average temperature $T_0$. This behavior is explained by the decrease of the thermal Rayleigh number due to the increase of gas viscosity caused by disordered motion of molecules [10, 11].

![Interferograms](image)

**Figure 5.** Interferograms indicating convection in dry air at $T_0 = 10$ C (a-d) and $T_0 = 50$ C (e-h) with different $\Delta T$ between the cooler (top) and the heater (bottom) of the measuring cell
Figure 6. Interferograms at different average temperature $T_0$ ($\Delta T = 20$ C is the same)

The digital images of interferograms (Figs. 5, 6) are further processed numerically in order to reconstruct the $\Delta n(x,y)$ differential refractive index field using Mathematica computer algebra system [6]. The refractive index field itself is not very informative, of course, because $n = n(T, c)$ is a function of both temperature $T$ and vapor concentration $c$ at once. Moreover, for humid air

$$\frac{\partial n}{\partial T} \approx \frac{\partial n}{\partial c},$$

so it is impossible to study thermal convection and concentration convection separately. The observed phenomenon is a complex thermoconcentration convection, and fortunately there is no need to split this process into two, because the direct comparison of experimental measurements for humid and dry air can clarify the qualitative role and quantitative value of the concentration Rayleigh number $Ra_c$ and its relative weight in the effective Rayleigh number $Ra_E = Ra_T + Ra_c$. Thus, $\Delta n(x,y)$ is useful for future comparison with the similar $\Delta n(x,y)$ data obtained in numerical simulations. It is very promising to compare experimental observations with numerical calculations not only in terms of thermocouple temperature measurements (performed in just a few points inside the cell as shown in the Fig. 2), but to get an overall comparison of the whole $\Delta n(x,y)$ field data.

Let us also discuss the next step of the present work. It is necessary to obtain similar results for moist air undergoing the first-order phase transition. New problem requires significant modification of the existing experimental setup, because condensation of vapor on the top (cold) heat exchanger causes intensive “rainfall” which can totally blur any interferogram. It was decided to solve the condensate circulation problem using the principle of heat tubes. It is well-known that heat tubes can work in any position (orientation), because the liquid coolant circulates inside such tubes due to capillary forces: the condensate returns to the evaporation zone through special pores or grooves inside the tubes. The similar technical solution was applied to the top heat exchanger (Fig. 7). The grooves were cut to forward the droplets of condensing water to the vertical textolite walls, along which they will flow down to the lower heat exchanger due to gravity force. The groove profile dimensions (period 2 mm, width 1 mm and depth 0.5 mm, see Fig. 7b) were calculated beforehand according to the capillary force curvature of the water surface. Approval test experiments with the standard copper CPU cooler were also performed before milling the main heat exchanger (Fig. 7a). It was demonstrated that such fluted surface effectively condensates vapor and forwards it to the side walls. Right at the moment the reconstruction of the experimental setup is finished and the test experiments with humid air a being started.
4. Conclusions

The paper describes the fundamental experiment, which is focused on the physical aspects of thermoconcentration convection in fluids, undergoing first-order phase transitions of the “gas-liquid” type. Humid air is used as a fluid for test experiments because of its significance for numerous applications, such as chemical industry and air circulation in the Earth’s atmosphere. It is shown that thermal convection and concentration convection of humid air can not be studied separately, because it is a common process of the thermoconcentration convection. The peculiar features of convection, caused by concentration changes of water vapor (as a result of its evaporation or condensation), are discussed in terms of dimensionless parameters. The couple of standard complementary experimental methods are used: holographic interferometry for visualization of convective flows and thermocouple method for heat flux measurements. Test experiments demonstrate and approve the design characteristics of the setup. The observations of convective flows in dehumidified air are demonstrated. Experimental setup is described in all details, including the original design of the cold heat exchanger (resembling a heat tube), proposed for next experiments with humid air.

References

[1] Chandrasekhar S 1961 Hydrodynamic and Hydromagnetic Stability (UK: Oxford)
[2] Martynenko O G, Khramtsov P P 2005 Free-Convective Heat Transfer (Berlin: Springer)
[3] Ogura Y 1963 Meteorol. Monogr. 5 65
[4] Arakawa A and Jung J H 2011 Atmos. Res. 102 263
[5] Derbyshire S H, Beau I, Bechtold P, Grandpeix, J Y, Piriou J M, Redelsperger J L and Soares P M 2004 Q. J. R. Meteorol. Soc. 130 3055
[6] Somov S A, Ivanov A S, Goncharov M M and Kondrashov A N 2021 J. Phys.: Conf. Ser. 1809 012033
[7] Shmerlin B Y and Kalashnik M V 2013 Phys. Uspekhi 56 473
[8] Hauf V and Grigul U 1973 Optical methods in heat transfer (Moscow: Mir) p 242
[9] Kikoin I K 1976 Tables of Physical Constants (Moscow: Atomizdat) p 1008
[10] Gershuni G and Zhukhovitskii E 1972 Convective stability of an incompressible fluid (Moskow: Nauka)
[11] Hirschfelder J O, Curtiss Ch F and Bird R B 1954 Molecular theory of gases and liquids (New York: Wiley) p 1219