EXPERIMENTS ON UP-SLOPE TO DOWN-SLOPE TRANSITION IN AN INCLINED BOX FILLED WITH WATER

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Summary The natural convection of water in inclined side-heated rectangular box is investigated experimentally and numerically. The aim is to demonstrate existence and features of the convective front formation typical for the evening transition of the atmospheric boundary layer on gentle slopes. Particle image velocimetry and thermometry allows for quantitative analysis of the temporary velocity and temperature fields generated in a small scale laboratory model. The laboratory experiment is compared with numerical simulations performed with Fluent. Observations confirmed predictions of the evening transition front described for the atmospheric flows by Hunt et al [1].

INTRODUCTION

Thermal circulation in a complex terrain is not yet fully understood and implemented in large scale atmospheric models. Theoretical models [1] and field observations [2] indicate presence of specific for the slope flow instabilities, like bellowing, "peeling off" and formation of stagnation fronts. These phenomena play an important role in a heat balance and mixing properties of the atmosphere in several urban regions, but they are underestimated or completely neglected in mesoscale weather prediction models. One of the least understood phenomenon is the flow transition in the evening. During the day, the flow is up-slope (known as the anabatic flow) and at night the flow occurs down the slope, (known as the katabatic flow). The transition from up-slope flow to down-slope flow occurs from half an hour to a few hours after the cooling of the ground begins. Recently Hunt et al. [1] developed an analytical model for the evening transition. It assumes that a fluid parcel starting at the bottom break of a slope, which is initially heated and supporting an up-slope flow, is subjected to a gradual cooling of the bottom in linear fashion. As the fluid parcels travel up-slope, they become regularly buoyant and finally stop. The stagnation surface of the fluid parcels take the form of a front which subsequently breaks down by heavy fluid parcels which lay above lighter particles behind the front. This new phenomena has amplifications in air pollution dispersion as the fronts can rapidly mix pollutants vertically and dilute them. Further, on bare lands, such fronts can enliven the dust, thus increasing particulate matter concentrations to unhealthy levels. The possibility of such formation was demonstrated in the laboratory by Hunt et al. [1], but they did not present information on how the temperature of fluid parcels vary along the slope and in direction normal to the slope. This gap is filled in the present study, where temperature and velocity are simultaneously measured using thermochromic liquid crystals tracers [3].

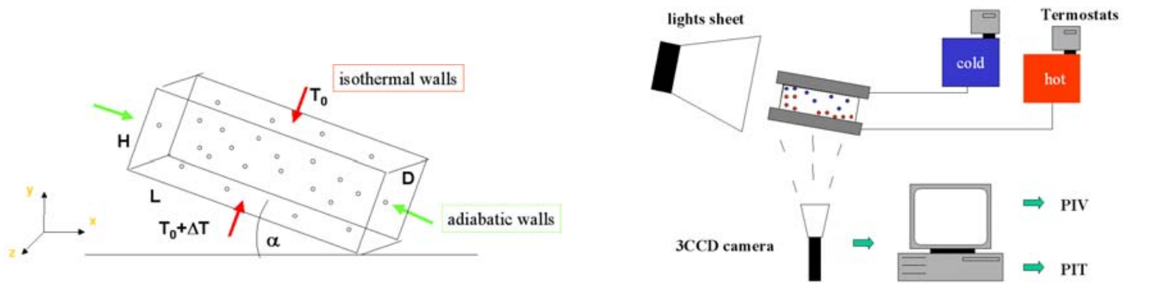
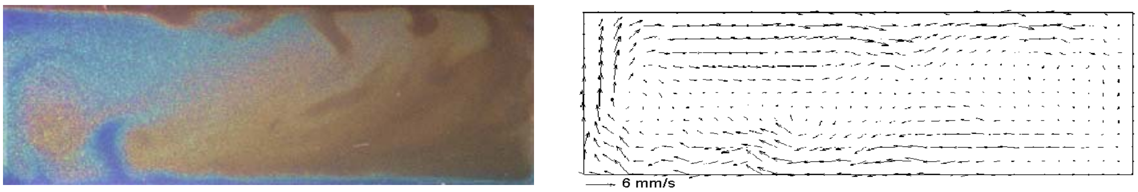


Figure 1. Schematic of the experimental apparatus: (a) – cavity, (b) – basic elements of the experimental rig

We consider natural convection in a rectangular, inclined box filled with water. The cavity has square cross-section 38 mm x 38 mm and is 114 mm high. The two side-walls are made from 7.5 mm thick Plexiglas. The other two isothermal side-walls are made of copper. The temperature of the isothermal walls is kept at 299K and 305K (ΔT=6K) by two heavy duty thermostats. To simulate up-slope flow a negative temperature gradient is set between the lower and upper wall (Fig. 1a). For transition and down-slope flow study the temperature of the walls is reversed by switching coolants settings. In the experiment it takes about 3min to equalize temperature of both walls and the next 3 min to stabilize the reverse temperature setting on the walls. The cavity inclination angle α is varied from 10^o - 30^o (Fig. 1a). The acquisition system (Fig. 1b) consists of a 3CCD colour camera and the 32-bit frame grabber (IC-PCI ITI). The flow field is illuminated with a 2 mm thin sheet of white light from a specially constructed halogen lamp, and observed in the perpendicular direction. Thermochromic Liquid Crystal (TLC) tracers changing colour of refracted light with temperature are employed to measure both temperature and velocity flow fields. The temperature measurements are based on a digital colour analysis of the flow images. The 2D velocity vector distribution is measured by digital particle image velocimetry (DPIV). By this method, the motion of the scattering particles, observed in the plane of the illuminating light sheet, is analysed by cross-correlating pairs of succeeding images. To get a general view of the flow pattern, several images recorded periodically within a given time interval have been added in the computer memory. Displayed images are similar to the multi-exposed photographs, showing the flow direction and its structure.

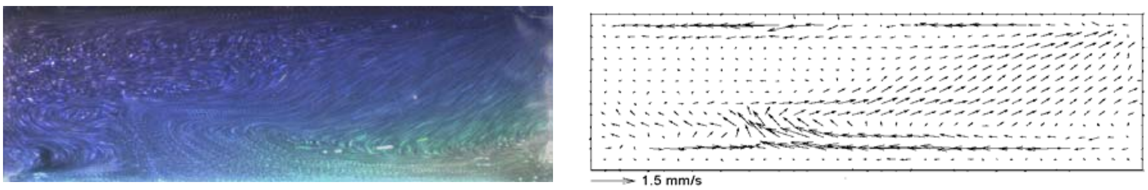
RESULTS

Experiments preformed for higher inclination of the box and larger temperature differences show onset of flow instabilities with periodically rising plums and hot fluid ejections, analogous to that observed for diurnal circulation on long sloping surfaces. Figure 2 shows visualization of the instantaneous temperature and velocity field acquired during ejection of the hot plum (blue colour) at the lower wall. These periodical ejections could be well identified in the experimentally measured velocity fields (Fig.2b) and reproduced in the numerical simulation. By increasing the temperature difference or inclination of the box this instability quickly gave rise to intense bulk flow mixing and equalisation of temperature in the core region. To avoid these effects our study of transition effects is limited to a low Rayleigh number, laminar up-slope flow. It was achieved by limiting the temperature difference to 6K and setting the inclination angle $\alpha = 10^o$. The corresponding Rayleigh number, based on the maximum height of the inclined cavity, is $8 \cdot 10^6$, just below the thermal stability limit. Figure 3 shows appearance of the transition front observed both in temperature field (colour of the tracers) as in the velocity field. The front builds up about 1 min after the reversal of temperature of the walls (4 min after reversal of the thermostats setting) at the distance of 2 cm from the lower edge of the slope, and it disappears about 5 min later, when regular "nocturnal" stratification of temperature and flow pattern develops. Hunt et al. [1] proposed time and length scaling of the front appearance, based on the parcels buoyancy, slope length and mean flow velocity. Using their scale we arrive to approximately 60s for the time scale and 1cm for the length scale. It appears that despite of the absence of turbulent mixing and presence of the flow disturbances created by the confined geometry, this scaling works yet pretty well for the laboratory experiment.



Temperature field Velocity field

Figure 2. Snap-shots of the temperature and velocity fields observed for the up-slope convection in the cavity; $\alpha = 20^o$, ΔT=6K.



Streak-lines Velocity field

Figure 3. Transition front observed 1min after temperature reversal; $\alpha = 10^o$, ΔT=6K.

Numerical simulations of the investigated experimental configurations were performed using finite-volume commercial code Fluent. Spatial derivatives were approximated using QUICK scheme and pressure-velocity coupling was done using SIMPLE algorithm. Solutions were obtained by direct simulation of the flow for two-dimensional, regular mesh with 480000 elements. The main futures of the experimental data like flow structure, temperature distribution, and velocity field appeared to be well reproduced in the numerical results. These initial validation of the numerical model opens possibility to use it for more profound parametric study of the occurrence of the transition front and its dependence on the geometry and temperature, in much wider variation of parameters than it is realizable in the experiment. Specifically numerical scaling of the problem to the environmental configurations will help us to find similarities useful for future building of the parameterisation necessary for weather prediction models.

References

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