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Research Paper

# Statistical analysis of turbulent thermal free convection over a small heat source in a large enclosed cavity

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## HIGHLIGHTS

- The detailed statistical analysis of temperature is carried out.
- Thermal boundary layers and fluctuation features are affected by edge effect.
- The center region of the cavity is less affected by edge effect.
- Temperature intermittent is huge where thermal plumes initially form and converge.

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## ABSTRACT

To investigate natural convection in an enclosed cavity, a rectangular experimental cavity is established. Transient temperature along the central line ($\boldsymbol{l}_1$) and the vertical axis of the longer side ($\boldsymbol{l}_2$) of the heat source is measured by using a T type thermal couple. Thermal boundary layers are presented. The center and border of the hot plate show different characteristics of thermal boundary layers and fluctuation features. The efficiency of energy transformation from large scales to smaller ones enhances with increased height and reaches an acme at the height of 5–8 mm, the juncture of thermal boundary layers. Flow field could be divided into three regions according to the analysis of power spectrum distribution (PSD). Numerical results show that the unsteady characteristics are extremely distinctive where the two thermal plumes initially form ($Z/H = 0.2$) and converge ($Z/H = 0.55$) because of edge effect. Thus, two peaks exist in the skewness and kurtosis of temperature.

## 1. Introduction

Natural convection has been applied in various fields, such as computers and automobiles [1–3]. Instabilities due to buoyancy caused convection when the heat flux exceeds a threshold. Hot fluid close to the hot wall, being lighter, tends to rise while cold fluid from the surroundings, being denser tends, to descend [4]. The most characteristic structure of fluid flow, resulting from buoyance induced convection, is a moving thermal plume, a jet-like upward motion of hotter fluid [5]. The near wall flow is characterized by a cyclic process, during which a conduction layer grows by diffusion, close to the heating surface, becomes unstable and erupts, forming a thermal plume by Howard [6]. Theerthan and Arakeri [7], based on experimental observations, proposed a different model assuming that near wall convection could be modeled as a periodic array of steady, laminar line plumes. Turbulent Rayleigh–Bénard (RB) convection – an enclosed fluid layer heated from below and cooled from above – is a classical model system that has long been used to study the complicated convection phenomenon [8–13]. Vouros and Panidis, based on experiments, studied turbulent thermal free convection over a horizontal heated plate in an open top cavity [14]. Sezai and Mohamad simulated natural convection from a discrete heat source on the bottom of a horizontal enclosure [15]. The characteristics of natural convection were analyzed both experimentally and numerically by Sheremet and colleagues [16–19]. Calcagni et al. dealt with the experimental results and numerical study of free convection in a square enclosure characterized by a discrete heater [20].

In a cabin full of persons, the problem includes the natural convection with discrete horizontal and vertical heated plates. Considerable attention has been paid to natural convection with discrete vertical heat sources [21–23]. However, few researches contribute to the investigation of natural convection over a discrete horizontal heat source of an enclosure. The purpose of the present work is to study the properties of turbulent thermal free convection over a discrete horizontal heated plate in a big closure cavity based on experiments and statistical analysis, and establish experimental data for related numerical simulation.

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## 2. Experimental setup

The cavity is 1960 mm × 980 mm × 800 mm, as shown in Fig. 1, and for the detailed information about the cavity, refer to the first paragraph of section 2.1 of the recently published paper by Zhang et al. [24].

The temperature measuring equipment is shown in Fig. 1. The accuracy of the motor-driven coordinate frame is 0.01 mm. The diameter of the thermocouple is 0.1 mm, much smaller than the Kolmogorov length scale $\eta = (\nu^3/\varepsilon)^{1/4} \approx 1.3\,\text{mm}$, where $\varepsilon = U^3/H$.

The real-time temperature series are stored in the computer with an accuracy of 0.25 °C by the National Instrument 9213 thermocouple module. The sampling frequencies of the present experiments are 50 Hz and 200 Hz, with response times of 0.02 s and 0.005 s, both smaller than the Kolmogorov time scale $\tau$ ($\tau = (\nu/\varepsilon)^{1/2} \approx 0.113\,\text{s}$). Thus, our apparatus is able to capture the real-time information of the temperature field. The measuring positions are shown as the red lines in Fig. 1. (For interpretation of the references to color in this text, the reader is referred to the web version of this article.)

In the present work, $T_c$ and $T_h$ are 20 °C and 40 °C respectively. As for the relevant non-dimensional numbers, we mostly focus on the Rayleigh number which is defined as:

$$Ra = \frac{\alpha g H^3 \Delta}{\nu \kappa}$$

In addition, the whole parameters are calculated based on the mean temperature between the cold and hot plates ($T_m = \frac{T_c + T_h}{2} = 30°\text{C}$). The Ra number is around $9.0 \times 10^8$ in the experiment.

## 3. Results and discussion

### 3.1. Temperature time series

From Fig. 2, temperature information of all measured positions can be captured and temperature is in the unit of degree Celsius. With the increase of height, the temperature near the heat source drops quickly and becomes quite unsteady. The temperature fluctuation near the cold plate is quite unsteady at the height of 780–795 mm and becomes steady at the height of 798–800 mm. All of the following results and discussions are based on the measured real-time information.

### 3.2. Average temperature and variance of temperature

In Fig. 3, the distribution of normalized mean temperature is presented. The mean temperature is normalized as $\Theta = (T_h - \overline{T_i})/\Delta$. Fig. 3 shows the temperature distribution along $\boldsymbol{l}_1$ and $\boldsymbol{l}_2$.

From the left sub-figure, we can see that the temperature gradient is extremely large near the hot and cold walls. Near the hot plate, most temperature drop occurs when z/H lies between 0 and $2 \times 10^{-3}$, with a very good linear character. The red dashed line near the heat source, the linear fitting of the normalized mean temperature, indicates the linear dependence of mean temperature close to the plate in the conduction layer, starting at z = 0. As the height continues to increase, in the mixing region, the temperature gradient becomes smaller. Most plumes mix, merge and cluster within this region. In the middle region, which is far away from both the hot and cold plates, nearly isothermal conditions prevail, with mean temperature gradient being almost zero, indicating that convection is dominant. As shown by the horizontal red dashed line, the temperature of the bulk of the fluid remains about 22.5 °C ($\Theta = 0.875$). However, as the height goes higher and is near the cold wall, the temperature continues to decrease. The temperature gradient starts to deflect from zero and becomes larger. The temperature close to the cold plate remains linearly dependent on the height, same with the region near the hot plate.

Specifically, turbulent convection can be divided into three regions, according to the distribution of mean temperature. In the first region – linear region, localized near the hot and cold plates – of a constant temperature gradient, heat can only be transferred by conduction. As the height increases, fluid flows away from the plate, the third region – far away from the two plates – nearly isothermal conditions prevail, with almost zero mean temperature gradient, indicating that convection is dominant. The second region, which lies between the first and third regions, is the transitional region, where rapid plume mixing occurs.

The thermal boundary layer thickness $\delta_{\Theta,h}$ is generally defined as the length at which the extrapolation of the linear portion of the normalized mean temperature equals the central mean temperature ($T_\infty$). We estimate $\delta_{\Theta,h}$ to be equal to 8.0 mm (z/H = 0.01) in our experiment near the hot wall.

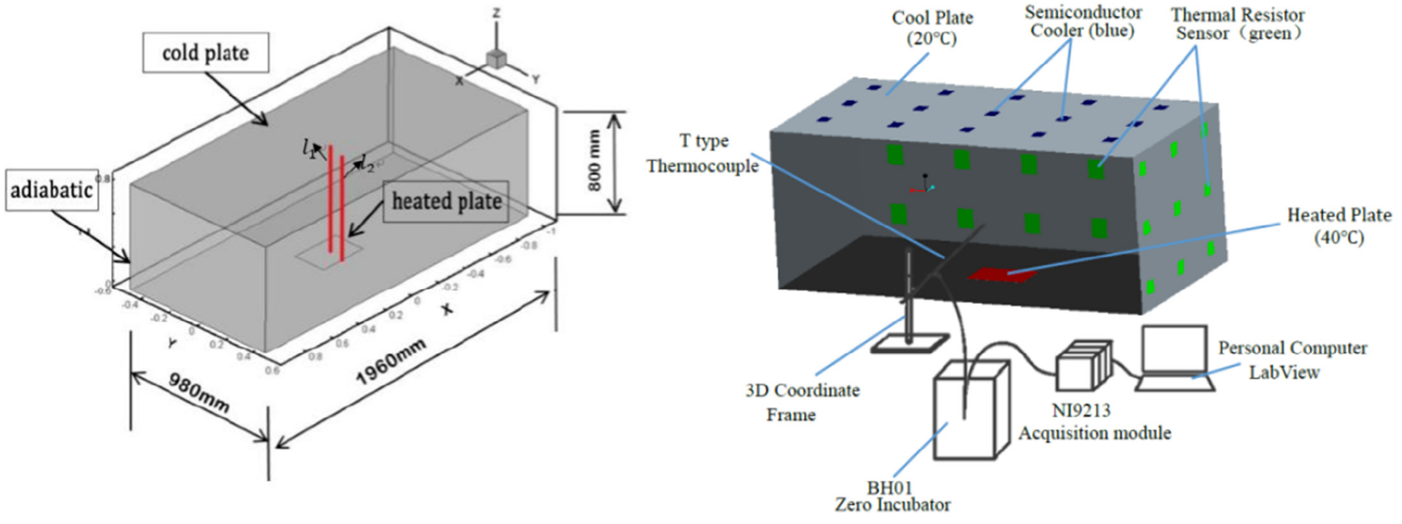

**Fig. 1.** The experimental cavity and measuring equipment.