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An experimental study of a starting plume on a mountain

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ABSTRACT

Transient natural convection is commonly present on a mountain owing to sun radiation. In this study, a starting plume rising from the mountain is experimentally investigated. Shadowgraph technology is employed to visualize transient natural convection flows on a heated copper mountain model in a water tank for a range of Rayleigh numbers from $Ra = 7.2 \times 10^6$ to 6.44×10^7. Transient flows on the mountain model can be characterized by a thermal boundary layer in the conduction stage and by the starting plume in the transition to a quasi-steady state. A very simple scaling analysis is used to discuss the dynamics of transient natural convection flows on the mountain model. The scaling relations of the thickness and the velocity of the thermal boundary layer and the starting plume on the mountain are obtained, some of which, for example, the velocity of the starting plume in the head velocity increase stage, $v_P \sim \kappa^2 tRa/h^3(1 + A^{-2})^{1/3}$, are validated by the experimental data. Additionally, the breaking of the plume head is described and quantified, and the flapping of the plume stem is also discussed.

1. Introduction

Plumes from localized heat sources are present in nature and in a number of industrial systems such as smoke releases, fires, volcanoes, waste disposal, cloud formation, and various other atmospheric and oceanic phenomena [1,2]. An understanding of plumes is important because of their relevance to flow problems over different scales. The quest for plumes has motivated numerous experimental, theoretical, and numerical investigations [3,4]. Naturally, the study of plumes on a point, line, or plane source with simple geometry has been an initial step for understanding the abovementioned flows.

The classical plume theory was presented by Batchelor [5] and Morton et al. [6]. Ordinary differential equations were used to quantify plumes including entrainment from the ambient fluid. Analytical solutions of a plume on a point or a line heat source are also obtained in [7,8]. Although Boussinesq's assumption is employed in the majority of theoretical studies, the non-Boussinesq effect, considerably existing in nature and industrial systems such as fire, has been discussed and the non-Boussinesq plume similarity solution has been obtained [9]. Plumes could be laminar or turbulent, and the primary influence of buoyancy on turbulence is through the mean velocity field of the plume [10]. Puffing and flapping are the prominent feature of turbulent plumes [11]. Here, flapping and puffing modes denote vortex growth on alternate sides and on simultaneous sides, respectively (see [4] for details). It has been demonstrated that puffing is usually associated with the instability of lapping flow on the heat source [12].

Studies (e.g., [13]) have further extended the classic theory and focused on a variety of plumes such as a starting plume, which was termed by Turner [14]. The study in [15] shows that the development of a starting plume undergoes through four different ascent stages: a conduction stage, a head velocity increase stage, a "plateau" stage where the head velocity remains constant, and a head velocity decrease stage. Moses et al. [16] pointed out that the fluid in the vicinity of the heat source is first heated following sudden heating. That is, conduction dominates natural convection around the heat source in the earlier stage. A starting plume of an axisymmetric structure appears when convection becomes sufficiently large. Subsequently, a head of the starting plume forms, develops, and even breaks [17,18]. The corresponding temperature and velocity have been measured in [19,20]. Studies (e.g., [21]) have also demonstrated that the plume head is first accelerated in the head velocity increase stage. However, this stage is very short in the case with a point or a line source, and thus difficult to study [22]. In the "plateau" stage, the velocity of a Gaussian profile in the crosswise dependent on the square root of the power has been measured for different Prandtl numbers, which is consistent with the scaling relation in [5] and the asymptotic solution in [22]. However, it is also clear that the velocity measured in the experiment is different owing to the temperature-dependent thermal expansion, conductivity and viscosity. Additionally, it can be expected that the head slows down owing to the presence of a free surface in the tank experiment. Because

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Nomenclature

A	aspect ratio
f	frequency (Hz)
g	acceleration due to gravity (m/s^2)
h	height of the mountain model (m)
Pr	Prandtl number
q	heat flux rate through the wall (W)
Q_T	flow rate of the plume (m^2/s)
Q_{Ts}	steady flow rate of the plume (m^2/s)
r	radius of the bottom of the mountain model (m)
Ra	Rayleigh number
S	surface area (m^2)
T	temperature (K)
T_h	temperature of the mountain model (K)
T_0	initial temperature of the fluid (K)
ΔT	initial temperature difference between the working fluid and the mountain surface (K)
t	time (s)
t_s	time when the thermal boundary layer becomes steady (s)
v_T	velocity of the fluid motion along the mountain surface (m/s)
v_{Ts}	velocity of the fluid motion along the mountain surface when the thermal boundary layer becomes steady (m/s)
v_P	velocity of the plume head (m/s)
v_{Ps}	velocity of the plume head at t_s (m/s)
x_P	x-coordinate of the plume stem (m)
y_b	height at which the plume head starts to break (m)
β	coefficient of thermal expansion (1/K)
δ	thickness of the tank wall (m)
δ_{PT}	thickness of the thermal plume stem (m)
δ_{PTs}	thickness of the thermal plume stem at t_s (m)
δ_T	thickness of the thermal boundary layer (m)
δ_{Ts}	thickness of the steady thermal boundary layer (m)

the mechanism is clear, the starting plume in the head velocity decrease stage is rarely investigated [15].

Recently, the shape and size of the heat source generating the plume have also been investigated owing to their variance in natural and industrial systems [23–25] in which the results obtained are compared with those in the case for a point or a line heat source. Nevertheless, the dynamics of the starting plume rising from a heat source with a complex geometry and a large size were rarely studied [15]. In fact, as the size of the heat source increases, the head velocity increase stage also increases. That is, the starting plume in the head velocity increase stage is more easily observed and measured in the case with a large size heat source such as a mountain. Additionally, the study [26] also indicates that transient natural convection flows are widely present in the mountain area. Accordingly, it is of practical significance to investigate the starting plume in the head velocity increase stage using an experimental mountain model in a water tank, which is the motivation of this study.

In this study, transient natural convection flows on a heated mountain model in a water tank are investigated based on shadowgraph images, and the starting plume in the head velocity increase stage is focused. The dynamics of natural convection flows on the mountain is discussed using a very simple scaling analysis and the corresponding scaling relations are obtained and validated by the experiment. The feature of the starting plume in the head velocity increase stage is characterized.

Section 2 describes the experimental setup. In Section 3, the thermal boundary layer attached to the mountain and the starting plume are characterized, the corresponding dynamics is discussed, and the breaking of the plume head and the flapping of the plume stem are quantified. Section 4 summarizes the major conclusions.

2. Experimental setup

A set of experiments were conducted in a water tank of the internal dimension 0.6 m × 0.6 m × 0.6 m, which was made of the 0.015 m Perspex sheet, as illustrated in Fig. 1(a). The mountain model, which is a 1 mm chromium-coated copper cone with an inclined surface length of 0.05 m and a bottom diameter of 0.05 m, was located at the center of the bottom wall of the tank. A hot water bath of 0.2 m × 0.2 m × 0.1 m was mounted under the mountain model and connected to a circulator with a temperature accuracy of 0.01 K; that is, the hot water was circulated between the water bath and the circulator during the experiment. When the experiment was started, the hot water, heated and maintained at a specified temperature, flooded against the lower surface of the mountain model above the water bath (see Fig. 1a). Further, the surface of the mountain model was also heated to the specified temperature T_h. Here, the specified temperature and in turn the temperature difference between the working fluid in the tank and the hot water in the water bath (or the surface of the mountain model) varied in different experiments; that is, the experiment can be carried out for different Rayleigh numbers owing to the variance of the temperature difference in this study. As the hot water suddenly flushed against the mountain model from below when the experiment started, a suddenly isothermal condition of the surface of the mountain model was established and in turn transient natural convection flows occurred above the mountain model. This condition is different from those in [15,16] in which a line and point heat source under the control of heat flux was employed. In addition, it is worth noting that the temperature of the upper surface of the mountain model here is approximated by that of

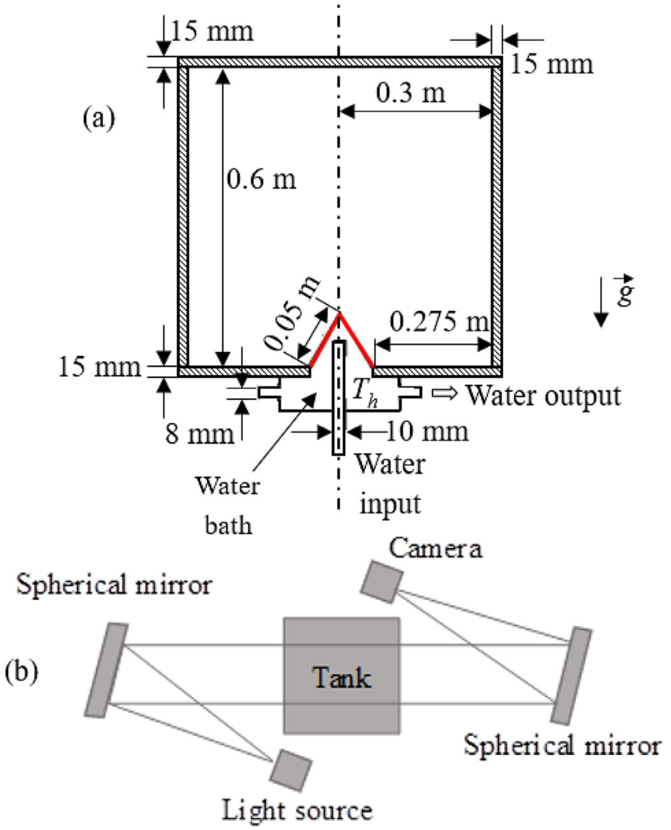

Fig. 1. Schematic of the experimental setup: (a) water tank; (b) shadowgraph system.