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Experimental investigation of the free convection velocity boundary layer and plume formation region for a heated horizontal cylinder

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ABSTRACT

Particle image velocimetry measurements were obtained in the free convection water flow around a heated horizontal cylinder for a Rayleigh number of 1.33×10^6 and a Prandtl number of 5.98. Radial and circumferential velocity were investigated within and just outside the velocity boundary layer in a vertical plane perpendicular to the cylinder axis. Radial and axial velocity were observed in the early plume development just above the top of the cylinder in a vertical plane parallel to and passing through the cylinder axis. The submersion depth of the top of the cylinder below the free water surface normalized by cylinder diameter ranged from $H/D = 2$ to 8, which includes depths for which the plume sways and meanders in periodic motion. The effects of plume swaying and meandering on the velocity boundary layer and plume formation were investigated. It was found that the approach flow outside the boundary layer was affected by penetrative convection caused by swaying and meandering of the plume even though there is no horizontal confinement. Measurements within the boundary layer as it nears the plume formation region and within the plume formation region itself reveal that penetrative zconvection in the approach flow altered the boundary layer and these effects propagated downstream into the plume formation region. The data therefore identified a feedback loop for which the plume fluid returns to the boundary layer sustaining the swaying motion. A direct cause of meandering was not determined.

1. Introduction

Free convection from a heated horizontal cylinder commonly occurs in heat exchangers, electronics cooling, and pipeline transport. Design of these applications is aided by detailed knowledge of the spatial and temporal dependence of the local heat transfer rate. To this end, a number of early investigations were aimed at measuring the heat transfer rate for a wide range of fluids and thermodynamic conditions, in large part for spatially averaged quantities obtained under steady conditions. Much of the data from these early investigations was used to develop frequently cited correlations between the two important nondimensional parameters: Rayleigh number, which quantifies the ratio of the buoyancy force to the viscous force, and Nusselt number, which represents the nondimensional temperature gradient at the cylinder surface. Correlations developed by Morgan [1] and Churchill and Chu [2] have gained wide acceptance, even though it was evident at the time that the data available in the literature included significant dispersion. Morgan attributed this dispersion to variations in the experimental conditions, such as different heat transfer boundary conditions at the axial endpoints of the cylinder, and also to the effects of physical confinement on the fluid surrounding the cylinder [1]. In the years leading up to the review by Morgan, vertical or horizontal confinement on the surrounding fluid were becoming recognized as significant factors that influenced the free convection heat transfer from the cylinder surface, thereby identifying the importance of the correlation between flow patterns away from the heated cylinder and the resulting free convection heat transfer rate at the surface. In this manner, it became clear that the boundary layer and the early plume development above the cylinder were not the only important regions of the flow field.

Prior to the development of these correlations, several studies identified periodic motion of the plume which might be one factor resulting in the dispersion in heat transfer measurements [3–6]. The periodic behavior is characterized by a swaying motion of the plume when viewed in a vertical plane perpendicular to the cylinder axis and, in some cases, a meandering motion, or a rippled structure of the plume in the axial direction when viewed from above. The characteristics of both periodic motions are provided in our previous investigation [7]. Since the initial reports of periodicity, plume swaying and meandering have been investigated both to understand how they affect the overall heat transfer from the

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Nomenclature

English symbols

A, B, C	image locations in the *xy*-plane
D	cylinder diameter
g	acceleration due to gravity
Gr	Grashof number
H	submersion depth between the top of the cylinder and the free water surface
Pr	Prandtl number
R	cylinder radius
r	radial coordinate with origin at the cylinder axis
Ra	Rayleigh number
T	temperature
t	time
v_r	ensemble-averaged radial velocity
$\bar{v}_r$	time-series-averaged radial velocity
v_θ	ensemble-averaged circumferential velocity
$\bar{v}_\theta$	time-series-averaged circumferential velocity
x	vertical Cartesian coordinate with origin at the top of the cylinder
y	horizontal Cartesian coordinate
z	axial coordinate

Greek symbols

α	thermal diffusivity
β	volumetric thermal expansion coefficient
δ	boundary layer thickness
ΔT	temperature difference between cylinder surface and quiescent water temperature
η	nondimensional radial distance with origin at the cylinder surface
ν	kinematic viscosity
σ	root-mean-square quantity
θ	circumferential coordinate with 0° at the bottom of the cylinder

Subscripts

0	starting time of a sway period
f	film quantity
r	radial quantity
s	cylinder surface condition
θ	circumferential quantity
∞	quiescent water condition

Superscripts

$*$	nondimensional

cylinder and to determine what features of the convective flow generate the periodic behavior as it is not always present. A review of the relevant experimental studies reveals that swaying is identified when the cylinder is submerged in a liquid with a free surface [7–15], in a liquid with some form of vertical confining surface [16–19] or in air with a vertical confining surface [20–24] provided the submersion depth is within a specific range [7,16,24]. If the vertical confinement is too close or too far from the cylinder, the regular periodic behavior ceases.

These experimental results agree with the findings in several numerical studies which simulate the flow on a time-dependent, two-dimensional basis [19,25–33]. Because the simulations modeled the cylinder within an enclosure, a factor of vertical confinement is common to all of them. Desrayaud and Lauriat provide a detailed report on simulated unsteady plume motion [28]. By varying the location of a line source within a square or rectangular enclosure, they were able to identify various flow instabilities and demonstrate a regular, periodic swaying motion of the plume. The plume motion was associated with penetrative convection, in which convective motion penetrates the stable layer of fluid below the line source. More recently Angeli and Pagano performed a thorough numerical study of the nonlinear dynamics of the two-dimensional plume rising from a heated horizontal cylinder centered in a square enclosure [33]. By varying the Rayleigh number over a wide range, they were able to determine a series of bifurcations that occur as the flow transitions to chaos.

From the experimental and numerical work, several features of the free convective flow have been associated with periodic motion. These features include instabilities present in the numerical findings [28,33], vortex formation along the side of the plume [11,13,21], and penetrative convection [10,11,28]. Even with the considerable number of investigations, the search for which flow features lead to swaying continues. This is evidenced by the differing conclusions in the recent works concerning free convective flow around two vertically aligned horizontal cylinders [17,18]. Because the plume swaying occurs only when the upper cylinder is present, Persoons et al. find that the upper cylinder imposes a form of vertical confinement which induces swaying, similar to the conclusions of some of the vertically confined works cited above. As part of their discussion, they propose that swaying may be caused by vortex formation on the sides of the plume near the upper cylinder or that it may be related to a Kelvin–Helmholtz instability similar to a cylinder in crossflow. Grafsrønningen and Jensen [18] present velocity and heat transfer measurements for two vertically aligned cylinders similar to the work of Persoons et al. [17] but at higher Rayleigh number. Grafsrønningen and Jensen also find the plume from the lower cylinder sways about the upper cylinder; however, in contrast to Persoons et al., Grafsrønningen and Jensen propose that the plume from the lower cylinder would likely sway without the presence of the upper cylinder and that the presence of the upper cylinder acts only to magnify the swaying motion [18]. Therefore, the debate over the cause of periodic motion remains.

Though flow instability, vortex formation, and penetrative convection are all associated with the swaying motion, there have been several findings in previous works that point to penetrative convection being the primary controlling factor for developing periodic motion [7,10,11,13,16,24,28]. As mentioned above, previous studies have shown that if the submersion depth of the cylinder below the vertically confining surface is too great or too shallow, regular swaying ceases [7,16,24]. In addition, the swaying period increases with larger submersion depth, which would correspond with the increased distance the plume fluid would have to travel to the upper surface and then return downward to the cylinder [7,13]. Finally, Urakawa et al. demonstrated that if fluid was added to a tank with a heated horizontal cylinder, swaying ceased, but if fluid was drained, swaying continued [13]. Filling the tank would keep the downward moving penetrating flow from reaching the cylinder to sustain swaying. These findings seem to imply that, although instability and vortex formation likely occur when swaying is not present, swaying is sustained only when penetrative convection is occurring.

Because of the importance of periodic plume motion to heat transfer and the continued uncertainty as to the cause of the motion, our previous investigation focused specifically on the plume motion above a heated horizontal cylinder to try to determine the mechanism within the flow that led to swaying [7]. From these measurements, we found characteristic features