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Numerical simulations of a line plume impinging on a ceiling in cold fresh water

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ABSTRACT

Laminar plumes from a line source of warm water at the base of a shallow, homogeneous body of cold water (below the temperature of maximum density) were simulated by a computational model. The plume water undergoes buoyancy reversal as it mixes with the cold ambient. If this occurs before the plume has reached the ceiling of the domain, the plume flaps from side to side. Otherwise, it spreads along the ceiling and then sinks, with a vortex enclosed between the rising plume and the sinking flow. Some of the dense, mixed water from the sinking flow is re-entrained into the rising plume, while the rest flows outwards along the floor. However, with high source temperatures, a sufficient volume of warm water eventually builds up to also form a positively buoyant gravity current along the ceiling.

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1. Introduction

Buoyancy-driven flows resulting from warm discharges into cold fresh water are of interest because of the possibility of buoyancy reversal due to the nonlinear relation between temperature and density in water. Mixing between the discharged water and the ambient may produce water that is denser than both the warm discharge and the cold ambient water, a process termed “cabbeling” by Foster [1]. For example, cooling water from power stations is typically discharged at a temperature approximately 10 °C above that of the receiving water [2,3]. If this receiving water is a lake below the temperature of maximum density (approximately 4 °C in fresh water), mixed water at temperatures close to 4 °C may be negatively buoyant and descend to the lake bed rather than spreading at the surface. This was the explanation proposed by Hoglund and Spigarelli [4] for the observation of water at a temperature of 5.7 °C at the bed of Lake Michigan in the vicinity of a power station outfall while the natural ambient temperature was 0.5 °C.

In the laboratory, Marmoush et al. [3] used lock-exchange experiments to simulate the flow resulting from a discharge of warm water into a cold lake. A series of experiments by Bukreev has involved various configurations of warm water discharge into a cold ambient. These have included classical lock-exchange [5] and a variety of other arrangements in which warm and cold water are brought into contact across a vertical plane [6,7]. Such experiments demonstrate clearly the effects of buoyancy reversal and the confinement of the flow by the upper boundary of the receiving water, but do not simulate the near-field of a discharge from an outfall, where the flow would be in the form of a buoyant plume or jet. Further experiments by Bukreev have involved injection of jets of warm water into a cold ambient, both horizontally [8] and vertically upwards [9]. In the latter case, buoyancy reversal occurred before the rising plume interacted with the surface of the receiving water, with the initially rising plume forming a fountain; this case, which is shown schematically in Fig. 1, was the subject of a computational simulation by George and Kay [10]. The case where a warm plume in cold water impinges on the upper surface before buoyancy reversal has halted its rise has not yet been addressed either experimentally or computationally. On reaching the surface, the warm water is expected to spread as a positively buoyant gravity current until buoyancy reversal due to mixing causes it to sink to the bed (Fig. 2); this behaviour has been seen in experimental studies of gravity currents in cold water [3,5–7].

Thus we may contrast the behaviour of free plumes and fountains (where there is no interaction with boundaries) with that of confined flows, where there is impingement on a ceiling or free surface. Parameters which control the behaviour of free plumes and fountains are the Froude number Fr and Reynolds number Re at the source, and the Prandtl number Pr of the fluid; alternatively, the Richardson number, $Ri = Fr^{-2}$, may be used instead of the Froude number. If there is a nonlinear temperature-density

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Nomenclature

c_p	specific heat capacity
Fr	Froude number
h	domain height
H	dimensionless domain height
k	thermal conductivity
l	domain width
L_{ad}	dimensionless spreading distance in upper part of domain
L_d	dimensionless spreading distance on ceiling
p	pressure
P	dimensionless pressure
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
t	time
T	temperature
u	horizontal velocity component
U	dimensionless horizontal velocity component
v	vertical velocity component
V	dimensionless vertical velocity component
x	horizontal coordinate
X	dimensionless horizontal coordinate
x_{in}	half-width of source
y	vertical coordinate
Y	dimensionless vertical coordinate

Greek letters

α	diffusivity of heat
β	coefficient in density-temperature relation
μ	viscosity
ν	diffusivity of momentum
ϕ	dimensionless temperature
ρ	density
τ	dimensionless time

Subscripts

in	source
m	maximum density
∞	undisturbed ambient

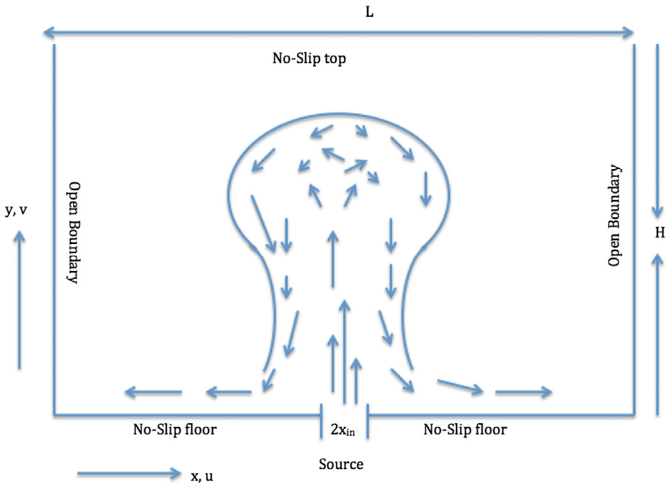

Fig. 1. Schematic of plume with buoyancy reversal, also showing domain for computations.

relationship, leading to buoyancy reversal, there will be a further control parameter, the dimensionless source temperature ϕ_{in} (defined below). Free plumes with buoyancy reversal have some similarity to fountains of negatively buoyant fluid, and recent research on free fountains was reviewed in [10]. The dependence on the control parameters of the maximum height of fountains and the time taken to reach that height has been studied, as well as the continuing unsteady behaviour ("flapping" and "bobbing") which occurs particularly in plumes with buoyancy reversal.

For confined plumes and fountains, the height H of the ceiling or free surface above the source (nondimensionalised with respect to the source half-width or radius) will constitute a further geometrical control parameter. A positively buoyant plume will spread along the upper boundary as a gravity current or "ceiling jet" [11]. However, studies of confined plumes have typically used "filling box" models [12] rather than considering the flow at the surface in detail, although there have been computational studies of natural ventilation flows involving plumes impinging on a ceiling with vents through which buoyant fluid may escape [13,14]. Confined plumes with buoyancy reversal may initially spread along a ceiling similarly to these positively buoyant flows, but will

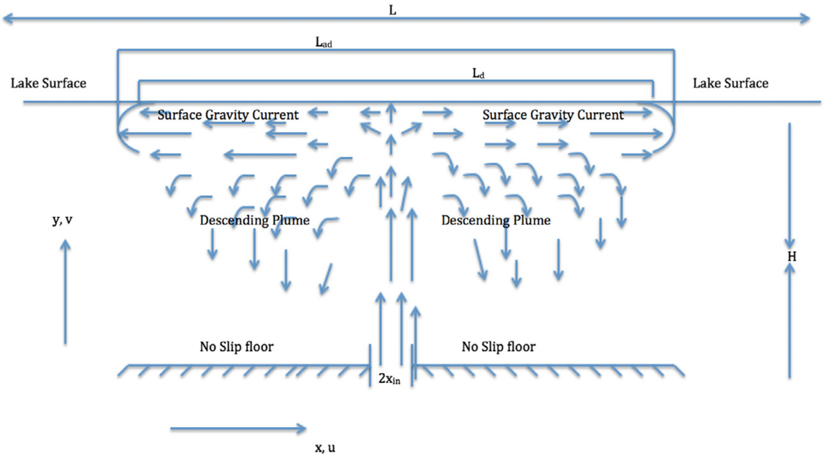

Fig. 2. Schematic of plume reaching lake surface before experiencing buoyancy reversal.

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