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Study of buoyant jets in natural ventilation of a model room

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ABSTRACT

Buoyant jets in natural ventilation of a model room with water as the fluid medium have been studied. A constant heat flux has been maintained on the bottom surface of the room. The buoyancy causes flow to enter through the bottom opening and leave through the top opening. The shadowgraph technique is used for visualization. At the inlet, a negatively buoyant jet is observed, whereas a positively buoyant jet is observed at the outlet. The theoretical results for the centerline trajectories of these buoyant jets using both Gaussian and top-hat profiles are discussed considering the variation of the entrainment coefficient with the local Froude number and the variation of the spreading ratio of buoyancy to velocity profile with the distance from the source. The shape of the profiles is found to evolve from top-hat to Gaussian geometry.

1. Introduction

Buoyant jets are encountered in many industrial and natural situations. Buoyant jets may be positively buoyant or negatively buoyant depending whether the discharge fluid is lighter or denser than the surrounding fluid. The effluent is positively buoyant in the case of domestic and industrial discharges into a marine environment. Positively buoyant jets have been studied extensively. Abraham's [1] study of three-dimensional horizontal jet show how the coordinates of the axis of the jet and the mixing rate and the velocity at the axis of the jet depend on the initial density differences between the jet and the ambient fluid and on the velocity of the jet when it issues from a nozzle. Anwar [2] studies behaviour of buoyant jet in calm fluid. According to this study, when a plume of light liquid is discharged horizontally or in a downward direction into a calm liquid of greater density, the plume rises in a curved trajectory to the surface, entraining the surrounding fluid. Dewan et al.[3] have developed a model for the integral analysis of laminar buoyant jets discharged horizontally. This model assumes top-hat density profile across the inner core of jet and Gaussian velocity profile. Their prediction of the jet trajectory agree well with experimental data in the regions where the jet remains laminar. Pantokratoras [4] uses a modified version of the integral Fan–Brooks model to calculate the horizontal penetration of inclined thermal buoyant water jets. Arakeri et al.'s [5] study for laminar buoyant jet discharged horizontally show bifurcation occurred in a limited domain of Grashof number and Reynolds number. Jones et al. [6] has developed a comprehensive classification framework for the variety of flow classes that can occur when a buoyant surface discharge occurs with variable geometry, momentum and buoyancy into a water body of variable depth and cross-flow strength. Jirka's [7] new jet integral model CorSurf for buoyant surface discharge addresses entire spectrum of jet motions in both deep or shallow environments.

The effluent from desalination plants, which have relatively high salinity concentrations, is negatively buoyant. Cavalletti and Davies [8] have studied the impact of vertical, turbulent, planar, negatively buoyant jet with rigid horizontal bottom boundary. Their study show that the impingement results in the generation of a complex two-dimensional disturbance field at the site of the impact and the generation of a buoyancy-driven boundary current carrying away fluid from the impingement zone. Querzoli and Cenedese [9] investigate the structure of a laminar negatively buoyant jet by means of both the laser induced fluorescence and the particle tracking velocimetry. They observe Kelvin–Helmoltz instabilities on the upper boundary of the jet. Kikkert et al. [10] have developed analytical solutions to predict the behavior of inclined negatively buoyant discharges and these solutions are compared with the experimental results using light attenuation and laser induced fluorescence techniques. Jirka [11] discusses an improved discharge configurations for brine effluents from desalination plants.

From the above studies, it is found that there is no combined study of positively and negatively buoyant jets in same platform. Also these buoyant jets are discussed mainly in calm environment.

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Nomenclature

a_L	area of the opening at leeward side
a_W	area of the opening at windward side
b	jet radius
C_e	co-efficient of losses at inlet
C_D	co-efficient of losses at outlet
D	diameter of the opening
Fr	Froude number
Gr	Grashoff number
g	acceleration due to gravity
g'	reduced gravity due to bouyancy
H	water layer height
h	vertical distance between openings
k	spreading ratio of buoyancy to velocity profile
Re	Reynolds number based on the size of the openings
Re_H	Reynolds number based on the height of the room
Ri	Richardson number
s	jet radius
T_i	temperature of the interior fluid
T_0	temperature of the jet at the source
T_c	jet centre-line temperature
u_c	jet centre-line velocity
u_0	velocity of the jet at the exit of the source
w	convective velocity scale
x	horizontal distance from the jet inlet
y	vertical distance from the jet inlet

Greek symbols

α	entrainment coefficient
β	thermal expansion coefficient
δ	extrainment coefficient
ΔT	room interior to exterior temperature difference
ΔT_b	room floor to interior temperature difference
κ	thermal diffusivity
ν	Kinematic viscosity
θ	inclination of the jet to the horizontal

In this paper, we have studied both positively and negatively buoyant jets in same platform using turbulent environment. This interesting phenomenon occurred at openings of a room during natural ventilation. Natural ventilation is an alternative low-energy solution to the ventilation problem in buildings. With natural ventilation, air movements occur because of pressure differences created by natural effects, either dynamic pressure differences due to the flow of the wind around a building, or static pressure differences due to the build-up of air within a building which is either warmer or cooler than the exterior (the stack pressure) or it may be due to both effects. In this natural ventilation, the pressure difference is due to the temperature difference between the interior and exterior ambient. In this study, the interior temperature is higher than that of the exterior; hence there is a negatively buoyant jet at the inlet and a positively buoyant jet at the outlet. In this paper, we will study the buoyant jets in a detailed way using both theoretical and experimental results. The theoretical analysis is given in Section 3. The laboratory modelling and scaling is discussed in Section 3 followed by the experimental set-up and the measurement details in Section 4. The theoretical results along with comparison with the experimental results are presented in Section 5.

2. Theoretical analysis: Gaussian versus top-hat profiles

The profiles of the buoyant jets at the inlet and outlet are studied theoretically using both Gaussian and top-hat profiles. The expressions found from the conservation of equations are used for both negatively and positively buoyant jets with some minor modifications. For the negatively buoyant jet at the inlet, there is an additional parameter, extrainment coefficient, due to interior convective environment, whereas this parameter is vanished for the case of positively buoyant jet at outlet. Also there is a change in sign for Richardson number, Ri, free convection to forced convection parameter, between these two jets. Here Ri is given by

$$Ri = Gr/Re^2 = g\beta(T_0 - T_i)D/u_0^2 \quad (1)$$

where Re is the Reynolds number for the buoyant jet given by u_0D/ν and Gr is the Grashoff number given by $g\beta\,(T_0 - T_i)D^3/\nu^2$. Here D is the diameter of the opening, u_0 is the velocity of the jet at the exit of the source, ν is the kinematic viscosity, T_0 is the temperature of the jet at the source, T_i is the temperature of the interior fluid, β is the thermal expansion coefficient and g is acceleration due to gravity. For the case of the positively buoyant jet at the outlet, the value of Ri is positive, whereas for the case of negatively buoyant jet at inlet, the value of Ri is negative.

First, we consider the top-hat profile for time averaged velocity and density differences across the plume, i.e. a uniform velocity across the plume and zero outside the plume. The equations of conservation of mass, momentum and buoyancy are, respectively,

$$\partial(b^2u_c)/\partial s = 2b\alpha u_c - 2b\delta w \quad (2)$$

$$\partial(b^2u_c^2cos\theta)/\partial s = -2b\delta wu_ccos\theta \quad (3)$$

$$\partial(b^2u_c^2sin\theta)/\partial s = g'(kb)^2 - 2b\delta wu_csin\theta \quad (4)$$

$$\partial(g'k^2b^2u_c)/\partial s = -k^2b^2u_c(g/\rho)\partial\rho/\partial y - 2kbg'\delta w \quad (5)$$

Here, x & y are the horizontal and vertical distances from the jet inlet respectively, s is distance along the jet centre-line, b is the jet radius, k is the spreading ratio of buoyancy to velocity profile, u_c is the jet centre-line velocity, α is the entrainment coefficient to the jet due to this centre-line velocity, θ is the inclination of the jet to the horizontal, w is the convective velocity scale, δ is the extrainment coefficient to the jet due to this convective velocity scale and g' is the reduced gravity (=$g\beta\Delta T$, where ΔT is a reference temperature difference). In the present case, since the density of the interior water is uniform throughout the water layer height, the first expression of the right hand side of the Eq. (5) will be eliminated. The expression for the w is given by [12] as follows

$$w = 0.43[(g\beta\Delta T_b)^4\kappa^2H^3/\nu]^{1/9} \quad (6)$$

Where H is the water layer height, ΔT_b is the temperature difference between the heated bottom plate and the interior water. After simplification of above equations (Eqs. (2)–(5)), we will get

$$\partial u_c/\partial s = g'k^2\sin\theta/u_c - 2\alpha u_c/b \quad (7)$$

$$\partial b/\partial s = 2\alpha - bg'k^2\sin\theta/2u_c^2 - \delta w/u_c \quad (8)$$

$$\partial\theta/\partial s = g'k^2\cos\theta/u_c^2 \quad (9)$$

$$\partial g'/\partial s = 2g'\delta w(k-1)/u_cbk - 2\alpha g'/b \quad (10)$$

$$\partial x/\partial s = \cos\theta \quad (11)$$

$$\partial y/\partial s = \sin\theta \quad (12)$$