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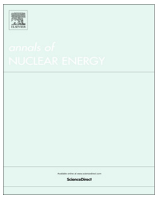

Modeling and experimental studies on air buoyant jets for application to small containments

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ABSTRACT

Small containments generally possess a small free volume and compact layout of inner structures. After a loss of coolant accident (LOCA) or main steam line break accident (MSLB), steam with high temperature and momentum may impinge directly on the safety-related equipment, which may harm the normal operation of these devices. Therefore, predictions of temperature and velocity of the jet are absolutely essential. Calculation model based on MATLAB and related experimental researches of hot-air to cold-air jet were carried out in this paper. Several typical experimental conditions have been simulated by the CFD code. The running time of these two codes proved the advantage of the model developed in this paper. Results of the calculations with the MATLAB model and CFD code are both coincident with the experimental data in general. Both modeling simulation and experimental results showed that temperature and velocity of the air jet decay rapidly in a limited distance and then the jet maintains a low temperature and velocity.

1. Introduction

During a loss of coolant accident (LOCA) or main steam line break accident (MSLB), vapors with high temperature and momentum will be injected into the containment. In the large containment, like that of an AP1000, the volume occupied by the jet is relatively small and can be ignored. Thermal mixing and stratification phenomenon plays a dominant role in affecting the heat removal of the containment. Peterson (1994), Peterson et al. (1998), Peterson and Gamble (1998) made scaling analysis about mixing and stratification in a large volume. Niu (2003), Niu et al. (2007) experimentally investigated the velocity field and thermal stratification in large enclosure. Zhao (2003) developed the BIMX ++ code for modeling the mixing and heat transfer problems in large stably stratified enclosures. Zhang et al. (2015) numerically studied the mixing and stratification in small scaled containment by, a new model and commercial software, ANSYS.

However, for the containment whose free volume is relatively small and structure compact, the effect of the jet itself cannot be neglected. Some key equipment may be exposed to the jet body area which could have adverse impact on the safety operation of such facilities. Therefore, prediction of the jet/plume temperature and velocity is necessary. Norman and Revankar (2011) investigated buoyant jet and two-phase jet/plume modeling. El-Amin et al. (2010) developed a non-Boussinesq turbulent buoyant jet model for low-density gas leaks into a high-density ambient. Jirka (2004) developed an integral model for turbulent buoyant jets in unbounded stratified flows. Rodi (1982) made a systematic introduction to the turbulent buoyant jet and plumes.

An integral non-Boussinesq buoyant jet model is developed in this paper to predict the variation of temperature and velocity in the jet body. Single phase hot-air to cold-air condition is considered and an energy equation accounting only for energy transport by turbulent mixing with the ambient cold air is used in this model. At the same time, experimental study using air instead of vapor was carried to verify the rationality of the current model. Several experimental conditions were calculated with a CFD code to substantiate the advantage of the integral model.

2. Basic theory and underlying assumptions for air jet modeling

In the ideal case of pure jet, the initial momentum flux is relatively high so that buoyancy can be ignored. In the pure plume, the initial velocity is assumed to be zero and the flow originates from a source of buoyancy. The buoyant jet or forced plume, which is produced with the influence of both initial momentum and buoyancy, falls in between the pure jet and pure plume. A 1-D integral model solving the centerline velocity and temperature of the buoyant jet is developed in this paper. The trajectory of the buoyant jet is

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Nomenclature

s	distance along vertical direction [m]
r	distance along r-axis [m]
b or $b(s)$	jet half-width [m]
u or $u(r,s)$	velocity at any point in the jet body [m/s]
u_{cl} or $u_{cl}(s)$	centerline velocity [m/s]
λ	buoyancy spreading factor [–]
ρ_∞	Ambient density used in calculation [kg/m^3]
ρ_i	initial ambient density [kg/m^3]
ρ or $\rho(r,s)$	density at any point in the jet body [kg/m^3]
ρ_{cl} or $\rho_{cl}(s)$	centerline density [kg/m^3]
η	correction factor for thermal-stratification [–]
V_e	entrainment velocity [m/s]
α	entrainment coefficient [–]
Fr	Froude number [–]
T or $T(r,s)$	temperature at any point in the jet body [°C]
h or $h(r,s)$	specific enthalpy at any point in the jet body [J/kg]
c_p	specific heat at constant pressure [J/(kg· K)]
h_∞	ambient specific enthalpy

shown in Fig. 1 in a simplified cylindrical coordinate system. The vertical axis (s-axis as shown in Fig. 1) across the center of the inlet is known as centerline and the buoyant jet flow is considered as axisymmetric that is symmetric around the centerline. Therefore, two components, axial component s and radial component r shown in Fig. 1, can fully describe the flow or thermal field in the jet.

For the water jet, Boussinesq approximation is invoked to some extent because the initial density difference, which is defined as, $\Delta\rho_0/\rho_\infty = (\rho_\infty - \rho_0)/\rho_\infty$ is negligible (Norman and Revankar, 2011; Rodi, 1982), where ρ_0 is the initial centerline density (density at the source) and ρ_∞ is the ambient density. However, in the case of air jet, the initial density difference is relatively high, so the Boussinesq approximation is considered to be invalid. According to El-Amin et al. (2010) and Crapper and Baines (1967), the upper bound of applicability of the Boussinesq approximation is that the initial density difference $\Delta\rho_0/\rho_\infty$ be 0.05. In general, the Boussinesq approximation can be used for small initial density difference, $\Delta\rho_0/\rho_\infty \ll 1$. The initial density differences in conditions, considered for this paper, range from 0.08 to 0.2, so Boussinesq approximation is assumed to be invalid. However, in the case of invalid Boussinesq approximation, the density variation must be taken into consideration. More discussions and studies are given by Spiegel and Veronis (1960) and Woods (1997).

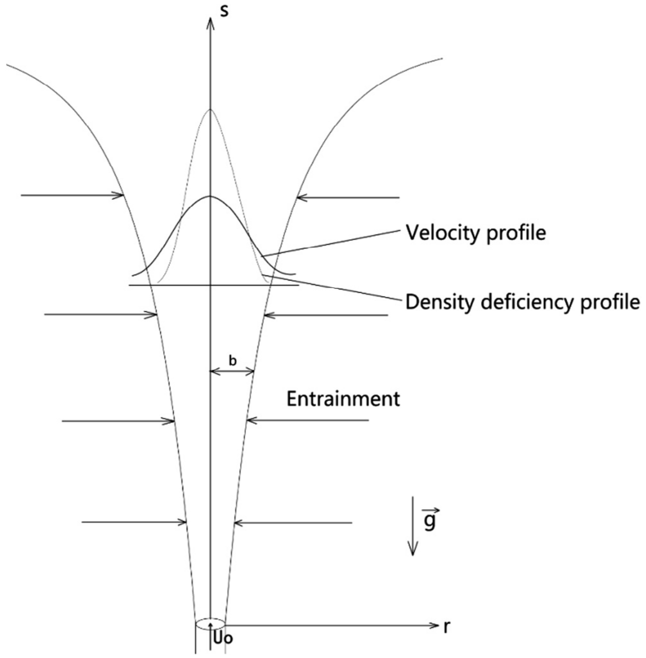

Fig. 1. Schematic of vertical injected air jet showing velocity and density deficiency profiles along the s-axis.

The air is assumed to be ideal gas. The pressure is taken as atmospheric pressure and it is assumed to be constant (1 atm) anywhere in the jet field. Therefore, the relationship between density and temperature of air can be determined by the isobaric expansion law,

$$T\rho = \frac{P_a M_a}{R} = constant \tag{1}$$

In the above equation, T and ρ respectively represent the temperature and density of air; P_a is the atmospheric pressure; M_a, which is the relative molecular mass of air, approximately equals 29 g·mol^{-1}; R is ideal gas constant, which is taken as 8.314472 m^3·Pa·mol^{-1}·K^{-1}. In addition, the air enthalpy is assumed to be in proportion to the local temperature (Norman and Revankar, 2011),

$$h(r,s) = c_p T(r,s) \tag{2}$$

where c_p is the specific heat at constant pressure. Considering the negligible variation of the specific heat, c_p is assumed to be constant as 1.006 kJ·kg^{-1}·K^{-1}. Therefore, combining Eqs. (1) and (2) gives,

$$h(r,s)\rho(r,s) = c_p \frac{P_a M_a}{R} = constant \tag{3}$$

The buoyant jet can be coupled with the surroundings by introducing a parameter called the entrainment coefficient (Norman and Revankar, 2011; Morton et al., 1956). It has been investigated by Batchelor (Batchelor, 1954) that a vigorous entrainment of the ambient will be produced as the density ratio tends to unity, $\rho_{cl}/\rho_\infty \to 1$, while as the density ratio tends to zero, $\rho_{cl}/\rho_\infty \to 0$, and there will be a smooth transition between the two limits. The experiments by Ricou and Spalding (1961) suggest that the entrainment assumption for the entrainment coefficient α, and arbitrary density ratio should be given in the form,

$$V_e = \alpha \left(\frac{\rho_{cl}}{\rho_\infty}\right)^{1/2} u_{cl} \tag{4}$$

where V_e is the inflow velocity at the jet edge which is called the entrainment velocity and α is the entrainment coefficient which is given by Jirka (2004), Jirka and Domeker (1991),

$$\alpha = 0.055 + \frac{0.6}{\mathrm{Fr}^2} \quad \text{with } \mathrm{Fr}^2 = \frac{u_{cl}^2 \rho_\infty}{g(\rho_\infty - \rho_{cl})b} \tag{5}$$

where *Fr* is the Froude number. The Froude number is a dimensionless number which shows the characteristic of the jet/plume. The pure jets possess a relatively large Froude numbers and the plume often has a small Froude number.

Investigations by Milgram (1983) showed that the velocity and density deficiency distributions across the buoyant jet