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Penetration behavior of opposed rows of staggered secondary air jets depending on jet penetration coefficient and momentum flux ratio

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ABSTRACT

A secondary air jet at an industrial combustor, such as an incinerator, has a strong effect on the gas-phase combustion and on the emission control of flue gases, such as CO and NOx, at the secondary combustion chamber. The secondary air's mixing performance is influenced by the jet configuration, including the orifice shape, size, and interval. In this study, we carried out a visualization experiment to analyze the penetration behavior of a secondary air jet system as a function of the jet penetration coefficient (*C*) and momentum flux ratio (*J*), based on previous research studies. We used a laser sheet beam and a fog generator to observe the penetration of the secondary air jet. The mass ratio of the secondary to the primary air was 0.24, and all experiments were carried out in atmospheric conditions. According to our experimental results, the penetration depth appeared shorter compared with the results of previously published research studies, which indicated that the optimum jet configuration with proper penetration of staggered jets occurs when *C* was equal to five. Results showed that the jets could not generate proper intersecting flow but collided at the center plane, indicating that the penetration depth was not enough for optimum mixing. The main differences in experimental conditions compared with the previously conducted research studies relate to the use of *J* values that are one order higher. The choice of *J* values induced high turbulence, and resulted in a high total viscosity, thereby obstructing the intersection of staggered jets. It also led to a smaller orifice size comparing to the duct depth. Therefore, a higher *C* value should be assigned to a higher *J* value of staggered jet configuration.

1. Introduction

Injection of secondary air exerts a governing influence on the residence time, flow pattern, and mixing performance of the combustion gas in the incineration system. Li et al. have studied the flow path and emissions according to the angle and flow rate of the secondary air, and over-fired air in a down-fired boiler [1–3]. Nasserzadeh et al. indicated that the modification of the secondary air orifice can help reduce emissions and optimize the overall plant performance of the incinerator [4,5]. The reduction of NOx emissions has also been achieved on the basis of the air staging conditions in the wall-fired boiler [6–8]. Some researchers described the importance of the secondary air jet configuration on the flow path and temperature distributions through CFD analyses [8–11]. Karagozian reviewed the transverse jet research studies related to single or multiphase jet flows that were focused on a single side jet [12].

Holdeman and Holdeman et al. [13,14] summarized the non-dimensional parameters that needed to be considered for designing the jet orifice at the gas turbine combustor, including the momentum flux ratio (*J*) and the optimum constant (*C*), subject to the following definitions:

$$\text{Momentum flux ratio,}\quad J = \frac{\rho_{jet} \times U_{jet}^2}{\rho_{main} \times U_{main}^2} \tag{1}$$

$$\text{Optimum constant (Penetration coefficient herein)},\ C = \left(\frac{S}{H_0}\right)\sqrt{J} \tag{2}$$

Holdeman [13] suggested that *C* is an essential design standard in determining the flow characteristics, such as mixing and uniformity of flow for the jet governing combustion system, and the jet penetration and the center-plane profile appear to be similar according to *C*. One of their core findings is the existence of an optimum condition for mixing and penetration, which is represented by *C*, as shown in Fig. 1. For single-sided cross-jet flow, the optimum *C* value is 2.5 because it can reach the center of the chamber.

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Nomenclature

List of symbols

A	penetration depth of the secondary air trajectory [m]
C	penetration coefficient
D	hydraulic diameter of orifice [m]
H	height of apparatus [m]
H_0	distance between right and left orifice box [m]
J	momentum flux ratio
MR	mass flow ratio of secondary to primary air
N	number of orifices at the left orifice box
RPD	relative penetration depth
ρ	density [kg/m^3]
ρ_{jet}	secondary air jet density [kg/m^3]
ρ_{main}	primary air density [kg/m^3]
S	distance between orifices [m]
U_{jet}	secondary air velocity [m/s]
U_{main}	primary air velocity [m/s]

For an inline, opposed, cross-jet flow, the optimum C value is 1.25 because it can penetrate a quarter of the entire depth of the chamber. In addition, for the staggered cross-jet flow, the optimum C value is five, leading to a 75% penetration of the entire depth. Because their theory indicates that C is related to the jet penetration depth, herein, we renamed C as the jet penetration coefficient.

Holdeman's study [13] focused on typical gas turbine combustors, and J values were in the range of 6–60. Meanwhile, the J values of conventional combustion chambers, such as the waste incinerator, are much higher than those of the gas turbine because the secondary air velocity takes values within the range of 60–100 m/s, whereas the main stream velocity is in the range of 1–4 m/s. Furthermore, the density of air is more than three times of the main stream density due to temperature differences. Hence, the value of J of the waste incinerator is usually one order higher than that of the gas turbine combustor. Correspondingly, the reported values of the ratio H_0/D in previous studies was in the range of 4–16, which is smaller than ours (24.4–60.7).

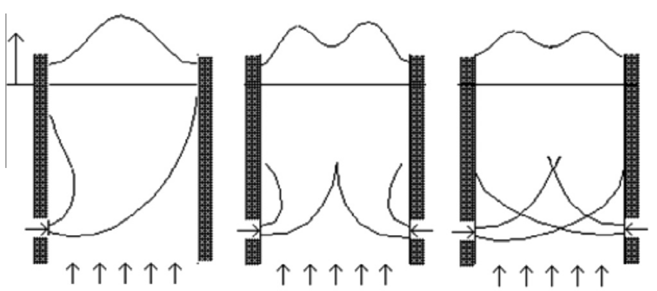

Fig. 1. The penetration of multiple jets: (a) single-side injection at $C = 2.5$, (b) opposed injection at $C = 1.25$, (c) staggered and opposed injection at $C = 5$ [13,16].

Bain et al.'s result using CFD showed that when the mass flow ratio of the secondary air jet to the primary air (MR) is larger than 1, then the optimum constant C increases for inline jet arrangements [15]. For example, C increases from 1.25 to 2–2.28 in the case when MR is 2. Meanwhile, Bain et al. also indicated that the staggered case does not change significantly (4–6.8 depending on J).

The present study assesses and extends the previous research to a combustion system, such as an incinerator, with a J value that is one order higher and larger H_0/D. To investigate the cross-jet flow of the staggered orifice, a scale down, cold-flow visualization system is utilized to identify the effect of J within a value range from 800 to 1600, and the effect of C within a range from 2.6 to 10.0.

2. Experimental methods

Fig. 2 shows a schematic of the experimental apparatus in which smoke was injected with a secondary air in order to visualize the flow pattern and the jet penetration of the orifices. Smoke has been photographed using a camera (Samsung 800 MP) and a diode pumped solid state laser (Civil Laser DPSS 1 W). The flow rates of the primary and secondary air were 0.125 m^3/s and

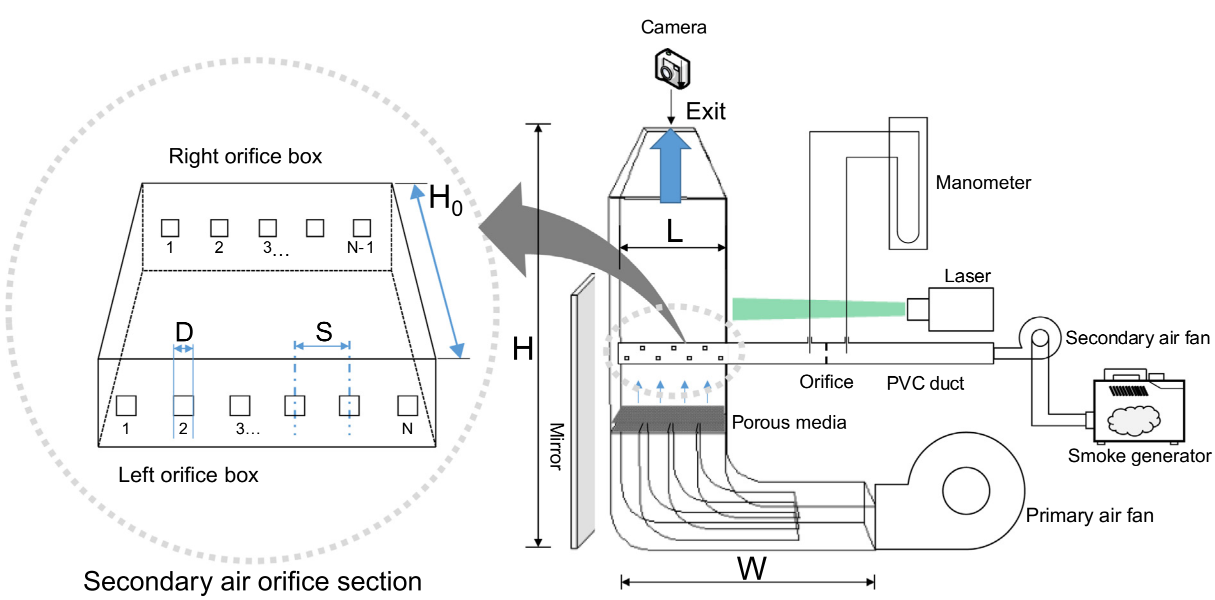

Fig. 2. Schematic diagram of the experimental system.