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Understanding the condensation process of turbulent steam jet using the PDPA system

Seungho Lim[a], Jinho Cha[a], Haneol Lee[a], Taejoon Kim[b,*], Weon Gyu Shin[a,*]

[a] Department of Mechanical Engineering, Chungnam National University, Daejeon 34134, South Korea
[b] Korea Hydro & Nuclear Power Co. Ltd., Daejeon 34101, South Korea

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ABSTRACT

In the present study, we investigated condensation characteristics of water droplets in a turbulent steam jet with the Reynolds number from 78,400 to 140,700, such as Particle Size Distribution (PSD), Total Number Concentration (TNC), and Liquid Water Content (LWC) obtained from the Phase Doppler Particle Analyzer (PDPA) system and measured the temperature profile. The temperature decay rate and the temperature half width ($r_{T,\,0.5}$) were obtained for steam jets. The increased latent heat release due to condensation was found to have an effect on the decreased temperature decay rate and the increased spread rate with an increase of the steam jet's Reynolds number. Along the radial direction at $z/d = 10$, TNC and LWC increased up to the range within $r\,/\,r_{T,\,0.5} = 1.2$, but the turbulence intensity continued to increase beyond the range. These results suggest that the evaporation effect started to occur due to the mixing with the surrounding air. Along the axial direction, we used the effective diameter in order to confirm the Reynolds number effect. As the Reynolds number became larger, particle formation started to occur further downstream along the axial direction. At the downstream of the peak position, the values of TNC and LWC were found to decrease due to the mixing process.

1. Introduction

Turbulent jets have been used in various engineering fields, including combustion, pollution dispersion, and vapor emission control of an industrial system (Darisse, 2013; Ghasemi, 2015; Vouros, 2013). In the power plants using high-temperature and high-pressure steam, condensation characteristics of turbulent steam jets are essential for the jets' operation safety and efficiency (Baskaya et al., 1998).

Depending on the momentum of the turbulent jet flow, the general structure of a turbulent jet can be divided, along its axial direction, into three regions. The first region is the near-field containing a potential core which keeps the initial condition flow and corresponds to $0 \langle z/d < 5$. The second region is the intermediate-field region where the turbulent jet is mixed with the ambient air and corresponds to $5 < z/d < 30$. The last region is the far-field region located at ca. $z/d \rangle 30$. The far field region is also referred to as the fully developed or self- similar region. The intermediate-field region lies between the near- and far fields of the jet. The location of each region of the turbulent jet may slightly vary depending on the initial conditions and boundary conditions of the jet discharged from the nozzle exit. The general structure of a turbulent jet flow along the radial direction is divided into three regions, namely, the centerline layer, the shear layer, and the outer layer. Three regions of a turbulent jet along the radial direction are determined through the mean velocity profile of jets with the turbulent fluctuation and entrainment with the surrounding air. In the centerline region, the maximum axial mean velocity of jets is found on the centerline. In the shear layer, the radial velocity gradient causes vortex cores to form, evolve, and pair to create large eddies. In the outer layer, the magnitude of the velocity is typically of order $U_c/10$ and rapidly falls to the free stream value (Abdel-Rahman, 2010; Abramovich, 1963; Ball et al., 2012).

When a turbulent steam jet is discharged into the atmosphere, the jet is mixed with cool ambient air. This causes the occurrence of complex phenomena, such as condensation of the steam jet, entrainment of ambient air, and evaporation of droplets. Therefore, the discharged turbulent steam jet becomes a mixture of three phases (water vapor, water droplets, and air). Numerous studies have focused on the characteristics of the turbulent condensing jet, such as entrainment rates (Baskaya et al., 1998), velocity distributions (Hinze and Zijnen, 1949), condensation process (Lesniewski and Friedlander, 1995, 1998; Oerlemans et al., 2001; Strum and Toor, 1992), and temperature distributions (Baskaya et al., 1997).

* Corresponding authors.
E-mail addresses: taejoon.kim@khnp.co.kr (T. Kim), wgshin@cnu.ac.kr (W.G. Shin).

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Nomenclature

z	axial coordinates (mm)
r	radial coordinates (mm)
U	mean velocity (m/s)
d	jet nozzle diameter (mm)
d_ε	effective diameter (mm)
Re	the Reynolds number
Pr	the Prandtl number
T	temperature (°C)
x	quality of steam
d_p	particle diameter (μm)
P_v	measurement volume of PDPA (μm^3)
k	exponent of the Gaussian fitting
C	the Gaussian constant
$r_{T,\,0.5}$	temperature half width (mm)
C_{SR}	spread rate of temperature
C_{DR}	centerline decay rate of temperature
z_o	virtual origin (mm)
P	pressure (kPag)
$\dot{m}$	mass flow rate (kg/h)
L	characteristic length (mm)
C_p	specific heat (J/kg K)
h_c	steam wall condensation heat transfer coefficient (W/m^2 K)
A	area of thermocouple probe (mm^2)
H_{fg}	latent heat (J/kg)
T_{TG}	temperature of thermocouple (°C)
T_{jet}	jet temperature (°C)
T_0	initial probe temperature (°C)

Acronyms

PDPA	phase Doppler particle analyzer
LDA	laser Doppler anemometry
OPC	optical particle counter
DBP	dibutyl phthalate
TVA	target variable area
TNC	particle total number concentration (#/cc)
LWC	liquid water contents (g/m^3)
PSD	particle size distributions

Greek Letters

ρ	density (kg/m^3)
μ	viscosity (Pa s)
θ	temperature difference (°C)
τ	response time (s)

Subscripts

amb	ambient
e	nozzle exit
c	centerline
v	vapor
w	water
0	supply condition
m	measurement point

For the condensing turbulent jet, the condensation process was investigated by using optical measuring instruments, such as PDPA, thermos-camera, Laser Doppler Anemometry (LDA), and the Fraunhofer diffraction technique. Strum and Herbert (1992) measured number densities, size distributions, and mean diameter of water droplets in the turbulent jet using the PDPA system. In their experiments, in order to obtain the mean diameter and number density, the water droplet formation was controlled by injecting seed particles into the jet (Re = 2246–2423). A comparison of the seeded condition with the unseeded condition showed that seeding moves the condensation towards a local thermodynamic equilibrium. Oerlemans et al. (2001) carried out an experimental investigation of turbulent steam jets varying nozzle diameters and initial velocities (Re = 3600–9200). The temperature, mean droplet velocity, and droplet sizes in a turbulent steam jet were measured using a thermo-camera, LDA, and the Fraunhofer diffraction technique, respectively. The local plate temperature represents the local wet-bulb temperature, which is close to the temperature of the droplets. The temperature measured by a thermos-camera was different from the vapor temperature of the jet. The droplet size was represented with the modal diameter, not with the size distribution. Oerlemans et al. (2001) concluded that the temperature difference between steam jets and ambient atmosphere is much larger than theoretical predictions for the single-phase jet, because the latent heat is released during the droplet formation process. In the condensation process, the droplet size becomes larger as long as the vapor is in the supersaturated state (Hinds, 1999). However, in Oerlemans et al.'s (2001) experimental conditions, the condensing jet becomes unsaturated, when it reaches an equilibrium to the far-field along the axial direction due to the continuous mixing with ambient air. In this position, the droplet size reaches its maximum size. As the initial velocity increases, the region becomes longer, while droplets are generated under the influence of the latent heat release. Therefore, as the initial velocity increases, temperatures become higher at the downstream, where the droplet size reaches the maximum size.

Baskaya et al. (1997, 1998) investigated the characteristics of steam jets with various initial conditions by using a thermocouple probe and the isokinetic sampling measurement technique. Steam jets were discharged into the ambient air under four nozzle exit conditions depending on the existence of choking and superheating (Re = 170,000–410,000). Baskaya et al. (1997) measured the temperature profile of the steam jet using a thermocouple probe. Using the temperature half width, the temperature spread rate was found to be in the range of 0.131–0.142. The temperature half width is the position where the radial temperature becomes the half of centerline temperature. The centerline temperature decay rate ranged from 0.017 to 0.037. In Baskaya et al.'s (1997) experimental condition, the initial velocity and initial temperature of saturated unchoked jet was lower than those of the superheated chocked jet. Therefore, the temperature spread rate of unchoked jets was smaller than that of chocked jets and the temperature decay rate of saturated jets was smaller than that of superheated jets. Furthermore, Baskaya et al. (1998) quantitatively investigated the mixing characteristics of turbulent steam jets, such as the spread rate and decay rate for the mass flow rate of air and steam. The spread rate of steam mass fraction for all cases was found to be ca. 0.085. The axial decay rate of steam mass fraction for the unchoked jet (0.098) was larger than the decay rate for the choked jet (0.091). In addition, Baskaya et al. (1998) investigated the entrainment rate by measuring the mass flow rate of both steam and air. The entrainment rate was found to be in the range from 0.243 to 0.389.

From a different perspective than the one adopted by Baskaya et al. (1998), under various initial conditions, Lesniewski and Friedlander (1995, 1998) investigated condensation properties, such as the particle nucleation rate and the total rate of particle formation through PSDs measured with an optical particle counter (OPC). Lesniewski and Friedlander (1998) investigated particle nucleation and particle formation in the shear layer of a discharged turbulent condensing jet. In Lesniewski and Friedlander's (1998) experiments, the nozzle diameters were 2.35 and 3.75 mm and the DBP vapor concentration was in the range from 100 to 500 ppm (Re = 4000–7000). When a heated nitrogen stream laden with the DBP vapor was discharged to particle-free air, as-