Mass Loading and Stokes Number Effects in Steady and Unsteady Particle-laden Jets

M.Eng. Science Thesis

Richard J. Foreman
The University of Adelaide
The School of Mechanical Engineering

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Abstract

In single phase, steady, turbulent axisymmetric jets, the time-averaged velocity field can be characterised by the decay in centreline velocity and increased spread with increasing distance from the jet orifice. In a two-phase or 'particle-laden' jet, the particles will modulate the jet turbulence and exchange momentum with the gas phase. Consequently, these effects reduce both the centreline velocity decay and spreading rates with respect to the single-phase jet. Empirical exponential scaling factors were found by previous authors to describe the reduced centreline decay and spreading rates well for low Stokes numbers. In this thesis, power-law scaling factors are found to scale well a wide range of centreline velocity decay and spreading rate data published over the past 40 years, for a wide range of Stokes numbers.

The power-law scaling is composed of three different regimes. For low Stokes numbers $St_o \lesssim 20$, it is found that the gas phase centreline velocity, u_o/u_c collapses if plotted as a function of $x/D(1+\phi_o)^{-1}$, and the velocity profile half widths $r_{1/2}$ collapse if plotted as a function of $x/D(1+\phi_o)^{-1}$. Here, u_o is the exit velocity, ϕ_o is the exit mass loading, x is the axial coordinate and D is the pipe diameter. For intermediate Stokes numbers, u_o/u_c collapses if plotted as a function of $x/D(1+\phi_o)^{-1}$ and $r_{1/2}$ collapses if plotted as a function of $x/D(1+\phi_o)^{-1/2}$. For high Stokes numbers $St_o \gtrsim 200$, u_o/u_c collapses if plotted as a function of $x/D(1+\phi_o)^{-1/2}$ and the half width is approximately independent of ϕ_o.

In addition to the velocity of the gas phase, other aspects of particle-laden jets are found to be amenable to scaling by power-law functions. It is found that reported solid phase mass flux data scales similarly to gas phase measurements. Limited solid phase concentration and entrainment measurements reported in the literature are also found to scale by power-law functions. Whereas that limited data was obtained from the literature, measurements of the distribution of particles in particle-laden jets were conducted to further assess the validity of the scaling regimes to the solid phase.

A planar light scattering technique is conducted to measure the distribution of particles in an axisymmetric jet and their subsequent scaling (or lack thereof) are reported for a variation in ϕ_o, Stokes number and gas phase jet exit density. For Stokes numbers based on the pipe friction velocity $St^*_o \sim 1$, half widths of particle distributions were found to scale with $x/D(1+\phi_o)^{-1/2}$. The apparent centreline concentration was found to be independent of ϕ_o at this same St^*_o. For Stokes numbers based on the pipe friction velocity $St^*_o < 1$, half widths are independent of ϕ_o. The effect of the other parameters, i.e. Stokes number and density ratio, on centreline distributions and half widths are also investigated.

Measurements of particle distributions, delivered via an annular channel, in a triangular oscillating jet (OJ) flow are also reported for a variation in momentum ratio, the ratio of OJ momentum to channel momentum and mass loading. The results of the variation in momentum ratio on particle distributions are compared with an existing precessing jet (PJ) study. It is the aim of this study to determine the experimental conditions for which the OJ nozzle is superior to the PJ nozzle. The use of an OJ nozzle is preferable at an industrial scale by virtue of its lower driving pressure compared with a PJ nozzle. It is found that particle distributions in a PJ flow spread at a greater rate with increasing momentum ratio compared with the spread of particles in an OJ flow. However, at momentum ratios approximately less than unity, the absolute spread from an OJ is greater. This also corresponds to nozzle driving pressure less than approximately 10kPA. For an increase in mass loading, the spread of particle distribution in the OJ decreases and recirculation increases.

Declarations

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Notation

A	Jet cross sectional area (m^2)
A_p	Probe cross sectional area (m^2)
a	Width of annular gap (m)
C_D	Drag coefficient
CTI	Change in turbulence intensity
D	Jet exit diameter (m)
D	Chamber diameter (m)
D_A	Inside annulus diameter (m)
D_n	Nozzle diameter (m)
D_o	Inlet orifice diameter (m)
d_1	Orifice diameter (m)
d_2	Exit lip diameter (m)
d_{43}	Volume weighted mean diameter (m)
d_e	Equivalent diameter (m)
d_p	Particle diameter (m)
F_p	Force on particle ($kgms^{-2}$)
F	Function
F_o	Characteristic scale
Fr	Particle Froude number
f	Similarity function
f_s	Light frequency (Hz)
f_d	Scattered light frequency (Hz)
f_d	Drag factor
G_1	Bulk mean momentum through central jet ($kgms^{-2}$)
G_2	Bulk mean momentum through annulus ($kgms^{-2}$)
h	Similarity function
K	Coefficient

K_1	Centerline decay coefficient
K_2	Spreading coefficient
K_2, n	Near field spreading coefficient
K_2, s	Strong side spreading coefficient
K_2, w	Weak side spreading coefficient
$\vec{k}$	Unit vector
L	Chamber length
$\vec{l}$	Unit vector
l_e	Characteristic eddy length scale (m)
M	Initial Jet momentum (kgms^{-2})
$\dot{m}_e$	Entrained gas mass flowrate (kgs^{-1})
$\dot{m}_f$	Gas phase mass flowrate (kgs^{-1})
$\dot{m}_p$	Solid phase mass flowrate (kgs^{-1})
$\dot{m}_{p,1/2}$	Solid phase mass flux half width (kgs^{-1}m^{-2})
$\dot{m}_{p,c}$	Solid phase centreline mass flux (kgs^{-1}m^{-2})
$\dot{m}_{p,o}$	Solid phase exit mass flux (kgs^{-1}m^{-2})
N	Number of particles
n	Exponent
P_d	Driving pressure (kPa)
p	Pressure (kgs^{-2}m^{-1})
p_∞	Ambient pressure (kgs^{-2}m^{-1})
Q	Volumetric flowrate (m^{3}s^{-1})
Re	Reynolds number
Re_p	Particle Reynolds numbers
R_{xu}	Correlation coefficient
r	Radial coordinate (m)
$r_{1/2}$	Half width (m)
$r'_{1/2}$	Half width calculated with respect to r/D_n = -0.15 (m)
$r'_{1/2,s}$	Strong side half width calculated with respect to r/D_n = -0.15 (m)
$r'_{1/2,w}$	Weak side half width calculated with respect to r/D_n = -0.15 (m)
r_l	Length scale (m)
r_{max}	Jet boundary (m)
r_{max}	Location of maximum signal (m)
S	Scattered signal intensity

S_c	Centreline signal intensity
$S_{c,o}$	Centreline signal intensity at jet exit
S_{max}	Maximum Signal
S_o	Signal at jet exit
$S_{o,a}$	Average signal at annulus exit
$S_{o,s}$	Strong side peak signal
St	Stokes number
St_m	Mean Stokes number
St_o	Exit Stokes number
St_o^*	Exit Stokes number based on the friction velocity
T_D	Signal period (s)
T_{dec}	Deceleration timescale (s)
t	Time (s)
U	Bulk mean exit velocity (ms^{-1})
U_2	Bulk mean exit velocity through annulus (ms^{-1})
$U_{2,max}$	Maximum exit velocity through annulus (ms^{-1})
u	Time averaged gas phase velocity (ms^{-1})
u'	Rms gas phase velocity (ms^{-1})
u^*	Friction velocity (ms^{-1})
u_c	Centerline velocity (ms^{-1})
u_o	Exit velocity (ms^{-1})
u_p	Time averaged solid phase velocity (ms^{-1})
u'_p	Rms solid phase velocity (ms^{-1})
V	Fluid volume (m^3)
V_p	Particle volume (m^3)
v	Time averaged transverse velocity in y direction (ms^{-1})
w	Time averaged transverse velocity in z direction (ms^{-1})
x	Axial coordinate (m)
x_n	Axial location of peak apparent centreline concentration (m)
x_p	Axial location of pinch-effect (m)
Δx	Fringe spacing (m)
y	Transverse coordinate (m)
z	Transverse coordinate (m)

Greek

η	Similarity parameter
θ	Angle between intersecting beams
λ	Laser light wavelength (m)
μ	Dynamic viscosity (kgm^{-1}s^{-2})
ν	Kinematic viscosity (ms^{-2})
ξ	Similarity parameter
ρ	Gas phase density (kgm^{-3})
ρ_j	Jet exit density (kgm^{-3})
ρ_p	Particle density (kgm^{-3})
ρ_a	Ambient fluid density (kgm^{-3})
σ_{sp}	Single phase turbulence intensity
σ_{tp}	Two phase turbulence intensity
τ	Reynolds stress (kgm^{-1}s^{-2})
τ_f	Fluid timescale (s)
τ_p	Particle timescale (s)
τ_{rec}	Recirculation timescale (s)
ϕ	Mass loading
ψ	Volumetric fraction