A STUDY OF A PLUNGING JET BUBBLE COLUMN

A thesis submitted for
the degree of
DOCTOR OF PHILOSOPHY

by

GEOFFREY MICHAEL EVANS

Department of Chemical Engineering
THE UNIVERSITY OF NEWCASTLE, N.S.W.

January, 1990

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

(Signed) Geoffrey Evans

ACKNOWLEDGEMENTS

I am indebted to my supervisor Professor G.J. Jameson for his advice, suggestions and support throughout the course of this study, and for providing me with the opportunity to be involved in the industrial application of fundamental principles of fluid mechanics.

I wish to thank the technical and workshop staff of the Department of Chemical Engineering for their assistance, especially John Marsh and John Richards for their work in building the experimental apparatus, and Robin D'Ombrain and Bronwyn Middlebrook for their assistance with the photography and computing aspects of the project.

Special thanks are given to Mr. Neil Molloy of the Department of Mechanical Engineering for many enlightening discussions on the entrainment of plunging jets, and also to Dr. Chris Rielly of Cambridge University, England for his advice on the expansion of confined submerged jets.

Finally, my deepest appreciation to my wife, Jennifer, for the typing of the thesis, and also the patience and understanding she has shown throughout the period of this study.

ABSTRACT

The hydrodynamic phenomena occurring inside the enclosed downcomer section of a plunging jet bubble column are described in this study.

The gas entrainment rate for a plunging liquid jet was found to consist of two components, namely the gas trapped within the effective jet diameter at the point of impact, and the gas contained within the film between the jet and induction trumpet surface at the point of rupture. Entrainment within the effective jet diameter has been examined by McCarthy (1972). In this study, a model has been developed to predict the rate of filmwise entrainment. The model was supported by the experimental results, provided the film attained a region of constant thickness. When the induction trumpet was ruptured prior to a constant film thickness being reached, the measured rate of filmwise entrainment was higher than the prediction.

Filmwise entrainment was found to be initiated once a critical velocity along the surface of the induction trumpet was reached. The critical velocity was a function only of the liquid physical properties and was independent of the jet conditions and downcomer diameter. The velocity of the free surface of the induction trumpet was obtained from the velocity profile for the recirculating eddy generated by the confined plunging liquid jet.

The jet angle used to describe the expansion of the submerged jet inside the downcomer was predicted from the radial diffusion of jet momentum into the recirculating eddy. The model was able to predict the jet angle when it was assumed that the radial diffusion of jet momentum was a function of the Euler number based on the jet velocity and absolute pressure in the headspace at the top of the downcomer.

The model was also developed to predict the maximum stable bubble diameter generated within the submerged jet volume, where the energy dissipation attributed to bubble breakup was given by the energy mixing loss derived for the throat section of a liquid-jet-gas-pump. Good agreement was found between the measured and predicted maximum bubble

diameter values. The average experimental Sauter mean/maximum diameter ratio was found to be 0.61, which was similar to that for other bubble generation devices.

It was found that for turbulent liquid conditions in the uniform two-phase flow region, a transition from bubbly to churn-turbulent flow occurred at a gas void fraction of approximately 0.2 when the gas drift-flux was zero. Under laminar liquid flow, this transition took place at a gas void fraction above 0.3.

For the bubbly flow regime the Distribution parameter C_o used by Zuber and Findlay (1965) to describe the velocity and gas void fraction profile, was found to be a function of the liquid Reynolds number. For laminar liquid flow, values of C_o greater than unity were obtained. As the liquid Reynolds number was increased it was found that C_o decreased, until a constant value of unity was obtained for fully turbulent flow.

For the churn-turbulent regime it was found that the gas void fraction measurements for all of the experimental runs could be collapsed onto a single curve when a modified gas void fraction was plotted against the gas-to-liquid volumetric flow ratio. The modified gas void fraction included a correction factor to account for the difference in the bubble slip velocity between the experimental runs. The experimental results also indicated that the value of the constant in the gas void fraction correction factor was different for laminar and turbulent flow.

Prior to bubble coalescence, it was found that the experimental drift-flux curves could be predicted from the measured bubble diameter, using the separated flow model developed by Ishii and Zuber (1979). After the onset of coalescence the drift flux measurements departed from the original drift-flux curves at a rate which increased linearly with increasing gas void fraction. It was found that the slope of the line fitted to the coalesced region of the drift-flux curves increased with increasing liquid Reynolds number and reached a constant value under fully turbulent flow conditions.

The model developed, together with the implications of the experimental results, are discussed with regard to optimising the design of an industrial plunging jet bubble column.

TABLE OF CONTENTS

Page

NOMENCLATURE

A	Area, (m^2)
b	Cross-sectional area ratio, (A_j/A_c)
C_o	Distribution parameter defined by (6.16)
D	Diameter, (m)
$\mathfrak{D}$	Dispersion coefficient, (m^2s^{-1})
d	Diameter, (m)
E	Energy dissipation rate, (kgm^2s^{-3})
e	Energy dissipation, (kgm^2s^{-2})
F	Force, ($kgms^{-2}$)
f	Friction factor
G	Circulation strength, (s^{-1})
g	Acceleration due to gravity, (ms^{-2})
J	Total volumetric flux, (ms^{-1})
j	Volumetric flux (or superficial velocity), (ms^{-1})
k	Frictional loss coefficient
L	Length, (m)
M	Momentum, ($kgms^{-1}$)
N	Number
P	Pressure, ($kgms^{-2}$)
Q	Volumetric flowrate, (m^3s^{-1})
R	Radius, (m)
r	Radial co-ordinate, (m)
S	Surface roughness (defined in Figure 4.4), (m)
T	Film thickness, (m)
T_c	Film thickness in constant film thickness region, (m)
t	Time, (s)
V	Volume, (m^3)

v	Voltage, (volts)
ν	Linear velocity, (ms^{-1})
W	Mass flowrate, (kgs^{-1})
y	Length from column wall, (m)
z	Axial length, (m)

GREEK SYMBOLS

β	Submerged jet angle, (degrees)
γ	Axis ratio, (length of maximum axis/length of minimum axis)
δ	Dirac delta function
ϵ	Gas void fraction
η	Energy transfer efficiency, (defined in 5.47)
θ	Nozzle contraction angle, (degrees)
χ	Film thickness ratio, (defined in 4.32)
μ	Absolute viscosity, (Pa-s)
ν	Kinematic viscosity, (m^2s^{-1})
Ω	Packing parameter, (used in 6.50)
ρ	Density, (kgm^{-3})
σ	Surface tension, (Nm^{-1})
τ	Shear stress, ($kgm^{-1}s^{-2}$)
ϕ	Angle of inclination from horizontal plane, (degrees)
ψ	Stream function
ω	Shear rate. (s^{-1})

SUPERSCRIPTS

*	Dimensionless quantity
'	Drift quantity

SUBSCRIPTS

B	Boundary layer
b	Bubble
c	Column
d	Droplet
e	Recirculating eddy
F	Film
f	Froth
G	Gas
I	Entrained gas component inside effective jet diameter
i	Interface
j	Jet
L	Liquid
M	Molecular
MZ	Mixing zone
m	Mean
N	Nozzle
o	Orifice
p	Pipe
r	Radial
S	Slip
s	Specific
T	Turbulent
VS	Volume-surface, or Sauter mean
w	Wall
z	Axial

DIMENSIONLESS NUMBERS

We	Weber number,	$\frac{\rho v^2 d}{\sigma}$.
Re	Reynolds number,	$\frac{\rho v d}{\mu}$.
Ca	Capillary number,	$\frac{\mu v}{\sigma}$.
N_H	Hill number,	$\frac{Q}{\sqrt{2\pi}\, r \sqrt{\frac{M}{\rho}}}$.
C_T	Crayer-Curtet number,	$\sqrt{\frac{2(N_H)^2}{1-(N_H)^2}}$.
Fr	Froude number,	$\frac{v^2}{gD}$.
N_{Eu}	Euler number,	$\frac{P_o}{v^2}$.