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Momentum Transfer in Multi-Jet Liquid-Gas Ejectors

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ABSTRACT

In a liquid-gas ejector the momentum of the liquid jet is utilised for intense mixing and dispersion of a gas in the liquid. The one dimensional homogeneous flow model proposed by earlier workers for the prediction of pressure distribution in the ejector was found to be valid only at low gas-liquid volume ratios. Since industrial gas-liquid transfer operations use much higher values of flow ratios, a non-homogeneous flow model taking into consideration the slip between the phases has been developed and tested against experimental data.

INTRODUCTION

Efficient dispersion of gases in liquids is of considerable importance in many engineering operations. In recent years increased interest is being shown in ejectors and other co-current devices for gas-liquid contacting because of advantages like low capital cost, simplicity of operation, low pressure drop and high capacity without flooding. In these systems the kinetic energy of a high velocity liquid jet is used to achieve fine dispersion and intense mixing between the phases. Zlokarnik (1980) reported an oxygen absorption efficiency as high as 3.8 kg/kwh in ejectors as compared to 0.8 kg/kwh in a propeller mixer. The higher energy efficiency of ejectors has been explained by Schugerl (1982) on the basis of the high fraction of microturbulence created.

Cunningham (1974) presented a one-dimensional homogeneous flow model for liquid-gas ejectors. This model assumes that the momentum transfer between gas and liquid is completed in the throat and a homogeneous mixture exits from the throat. The present work was undertaken to test the validity of the model at high volumetric gas flow rates and to propose a suitable momentum transfer model valid under all ranges of gas flow rate.

ONE DIMENSIONAL HOMOGENEOUS FLOW MODEL

The momentum transfer equations developed by Cunningham (1974) can be summarised as :

Mixing Throat :

$$P_o - P_t - \frac{L_t g \rho_l (1+\gamma\phi_o)}{1+\phi_t} = H\left[\frac{(2+K_{thf})(1+\gamma\phi_o)(1+\phi_t)}{A_R^2} - \frac{2}{A_R} - \frac{2\gamma\phi_o^2}{A_R(A_R-1)}\right] \qquad (1)$$

Divergent Diffuser :

$$P_d - P_t + P_o\phi_o \ln\frac{P_d}{P_t} = H\frac{(1+\gamma\phi_o)}{A_R^2}(1+\phi_t)^2(1-K_{dif}) - a^2_d(1+\phi_d)^2 - \rho_l(1+\gamma\phi_o)L_d \qquad (2)$$

The experimental pressure distribution data from an ejector was analysed by using the above equations to obtain the loss efficients K_{thf} and K_{dif}. The variation of these loss coefficients with the flow ratio are shown in Fig 1 and 2 respectively.

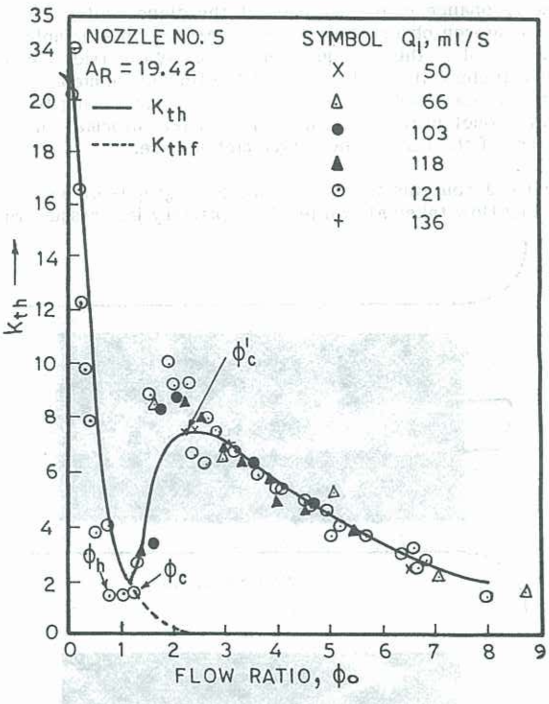

Fig 1 : Variation of loss coefficient K_{th} calculated from homogeneous Flow Model with flow ratio.

If these loss coefficients calculated from experimental data where true frictional coefficients K_{thf} and K_{dif}, one would expect them to be essentially constant. Cunningham (1974) found for a horizontal ejector such constant value over a small range of flow ratios between 0.5 and 1. He found that at higher flow ratios the K_{thf} values showed an increase, reached a maximum and then decreased. The coefficient K_{dif} remained constant over the same interval, after which it showed a minimum. In the present case with a vertical ejector the

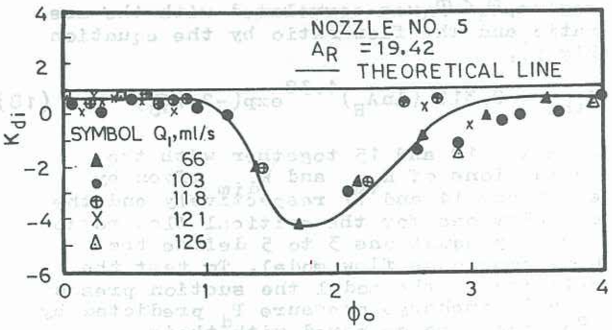

Fig 2 : Variation of loss coefficient K_{di} calculated from homogeneous flow model with flow ratio.

K_{di} values sharply decreased at low values, remained constant over a very small interval and then increased to reach a maximum. This behaviour of the frictional coefficient is perhaps because of the invalidity of the model over the total range of flow ratios.

REGIMES OF OPERATION OF A VERTICAL EJECTOR

By an analysis of the available momentum transfer rate in an ejector and the rate required to reach no slip condition, Radhakrishnan (1979) identified the following regimes in the operation of a vertical ejector. (see Fig 1)

1. $0 < \phi_o < \phi_h$

At low flow ratios the ejector is flooded and the momentum of the liquid jet is mostly expanded as impact losses. At $\phi_o = 0$, no useful work is done and the loss coefficient corresponds to that in a sudden expansion from nozzle area to throat area. With increasing secondary flow more and more useful work is obtained with consequent reduction in the frictional loss.

2. $\phi_h < \phi_o < \phi_c$: In this range the momentum transfer is completed in the throat and a homogeneous mixture leaves the throat. This is the range of validity of the homogeneous flow model.

3. $\phi_c < \phi_o < \phi_c'$: In this range the available rate of momentum transfer is less than the required rate and hence there is slip between the phases at the throat exit. The deficiency in the rate reaches a maximum at $\phi_o = \phi_c'$.

4. $\phi_o > \phi_c'$: The rate deficiency progressively decreases till $\phi_o = A_R-1$ when gas and liquid enter the throat at the same velocity. Hence the system is again homogeneous. Radhakrishnan (1979) has presented the following values for the critical flow ratios based on experiments covering nozzle area ratios 7-58, and flow ratios 0-9.

$$\phi_h = 0.5 \tag{3}$$

$$\phi_c = (A_R-1)/16 \tag{4}$$

$$\phi_c' = (A_R-1)/8 \tag{5}$$

The agreement between the experimental values of ϕ_c and ϕ_c', with those calculated from equation (4) and (5) is shown in Fig 3.

The assumption of no slip implicit in the homogeneous model is valid only over a

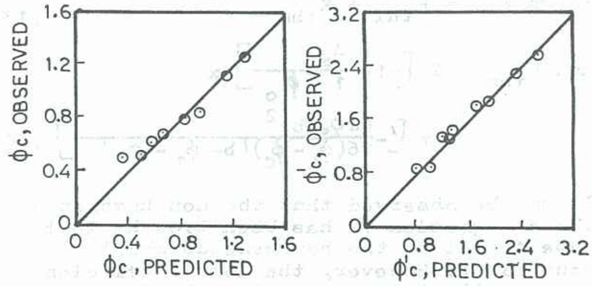

Fig 3 : Comparison between experimental and predicted values of the critical flow ratios.

narrow range of flow ratios between ϕ_h and ϕ_c. When we apply the homogenous model under conditions in which the momentum transfer is not complete in the throat, we are in effect attributing the non transferred energy to frictional losses in the throat. This causes the abnormal increase in the calculated values of K_{thf} and corresponding decrease in K_{dif} as shown Fig 1 and 2.

ONE DIMENSIONAL NON-HOMOGENOUS FLOW MODEL

The momentum balance equation for the mixing throat (Fig 4.b) may be expressed as,

$$m_1(V_{10}-V_{1t})-m_2(V_{2t}-V_{20})+(P_o-P_t)A_t-\tau A_w-F_g = 0 \tag{6}$$

Referring to Fig 4.b liquid and gas streams enter the throat at velocities V_{10} and V_{20} respectively. Momentum is transferred from liquid to gas. Since homogeneity is not reached the streams leave at velocities V_{1t} V_{2t} respectively, where,

$$V_{10} > V_{1t} > V_{3t}$$

$$\text{and } V_{20} < V_{2t} < V_{3t} \tag{7}$$

Assuming a linear velocity distribution we get from Fig 4.d

$$\frac{V_{2t}-V_{20}}{V_{3t}-V_{20}} = \frac{V_{10}-V_{1t}}{V_{10}-V_{3t}} \tag{8}$$

The mixture is homogeneous under two conditions, the first being at $\phi_o = \phi_c$ and the second when the two streams enter the throat at the same velocity, that is $\phi_o = A_R-1$. Therefore, $V_{1t} = V_{3t}$, when $\phi_o = \phi_c$ or $\phi_o = A_R-1$. Further, at $\phi_o = \phi_c'$ the slip is maximum and V_{1t} can be assumed to be equal to V_{10} as a first approximation. To satisfy these limiting conditions, as well as the experimental data, the following functional form was chosen to relate V_{1t} with V_{3t} and V_{10}

$$V_{1t} = V_{3t} + (V_{10}-V_{3t}) \times \exp \frac{-(4\phi_o-b)^2}{16(\phi_o-\phi_c)(b-\phi_o-\phi_c)} \tag{10}$$

The body force F_g may be approximated by,

$$F_g = \rho_{3t} L_t . g . A_t \tag{11}$$

Substituting equations 8,10 and 11 in equation 6 we get

$$P_o-P_t-\frac{L_t g \rho_1(1+\gamma\phi_o)}{1+\phi_t} = H\left[\frac{(2+K_{th})(1+\gamma\phi_o)(1+\phi_t)}{A_R^2} - \frac{2}{A_R} - \frac{2\gamma\phi_o^2}{A_R(A_R-1)}\right] \tag{12}$$

where $K_{th} = K_{thf} + K_{thm}$ (13)

and $K_{thm} = 2\left[-1+\frac{A_R}{1+\phi_o}\right] x$

$$\exp\left[-\frac{(4\phi_o-b)^2}{16(\phi_o-\phi_c)(b-\phi_o-\phi_c)}\right] \quad (14)$$

It may be observed that the non homogeneous throat equation 12 has been brought to the same format as the homogeneous model equation 1. However, the loss coefficient K_{thf} in the later accounts only for the frictional loss. In equation 12 the coefficient K_{th} contains the frictional loss and a term K_{thm} to account for unaccomplished momentum transfer.

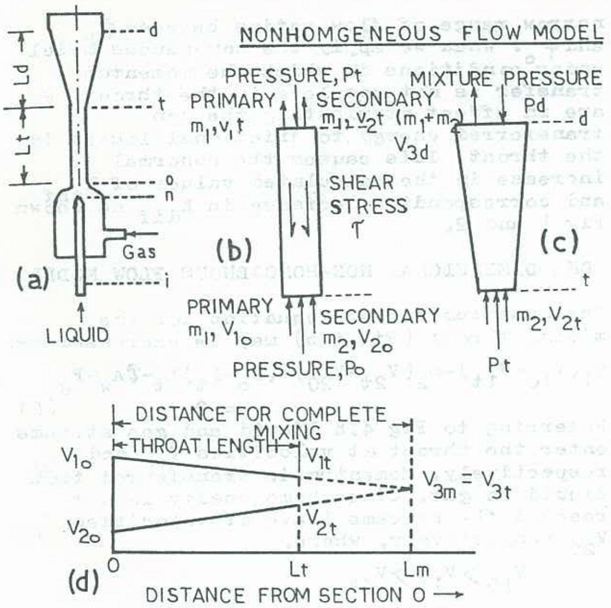

Fig 4 : Schematic diagrams related to analytical model.

By a similar energy balance analysis (Fig 4.c) the nonhomogeneous flow model equation for the diffuser may be derived as,

$$P_d-P_t+P_o\phi_o \ln\frac{P_d}{P_t} = \frac{H(1+\gamma\phi_o)}{A_R^2}\left[(1+\phi_t)^2(1-K_{di}) - a_d^2(1+\phi_d)^2\right] - \rho_l(1+\gamma\phi_t) g L_d \quad (15)$$

where $K_{di} = K_{dim} + K_{dif}$ (16)

and $K_{dim} = 1-\left[1+\left\{\frac{A_R}{(1+\phi_o)}-1\right\} x\right.$

$$\left.\exp\left\{-\frac{(4\phi_o-b)^2}{16(\phi_o-\phi_c)(b-\phi_o-\phi_c)}\right\}\right]^2 \quad (17)$$

EXPERIMENTAL

The model was tested by extensive experimentation with a vertical ejector. Radhakrishnan and Mitra (1984) has presented the details of the experimental apparatus. Fourteen different nozzles in the range of area ratios 7 to 58 were used. Experiments were conducted with water as the motive fluid and air as the secondary fluid. Flow ratios upto 9 were employed.

MODEL VALIDATION AND CORRELATION

The loss coefficient K_{thf} in the flooded regime, $\phi_o < \phi_h$ was correlated with the area ratio and the flow ratio by the equation (Fig 5),

$$K_{thf} = 0.311\,(\ln A_R)^{4.38}\exp(-2.7\phi_o) \quad (18)$$

Equation 12 and 15 together with the definitions of K_{thm} and K_{dim} given by equations 14 and 17 respectively and the correlations for the critical flow ratios given by equations 3 to 5 define the non-homogenous flow model. To test the validity of the model the suction pressure P_o and discharge pressure P_d predicted by the model are compared with their experimental values in Figures 6(a) and (b) respectively.

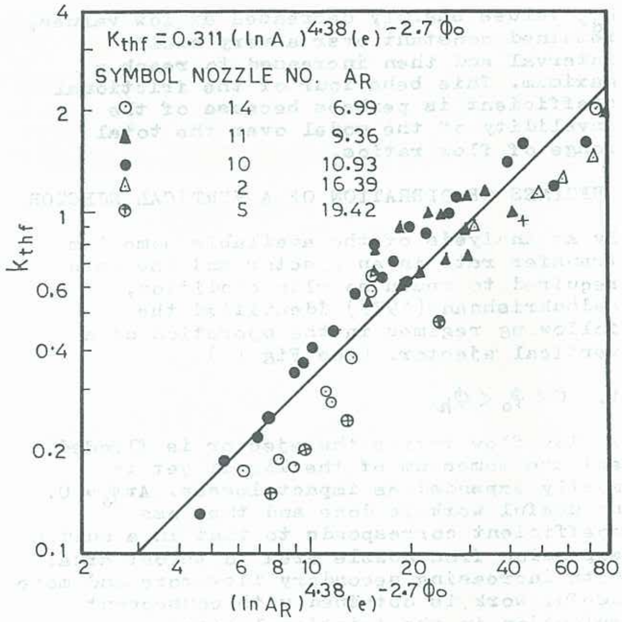

Fig 5 : Correlation for loss coefficient in flooded regime.

CONCLUSIONS

The assumption of no slip at the throat exit is not valid at high flow ratios. Formulation of the momentum transfer equations without this assumption leads to the non homogenous flow model. This model together with the correlations presented can predict the pressure distribution in the vertical ejector over a wide range of flow ratios.

NOMENCLATURE

a_d	divergent diffuser area ratio, A_t/A_d
A_d, A_t	cross-sectional area at sections d and t respectively (Figure 1a), m^2
A_R	Area ratio, A_t/A_n
A_w	parallel throat wall area, m^2
b	ratio $(A_t-A_n)/A_n$
F_g	gravitational force, N
g	acceleration due to gravity, m/s^2
H	jet velocity head, $V_{10}^2/2$, N/m^2

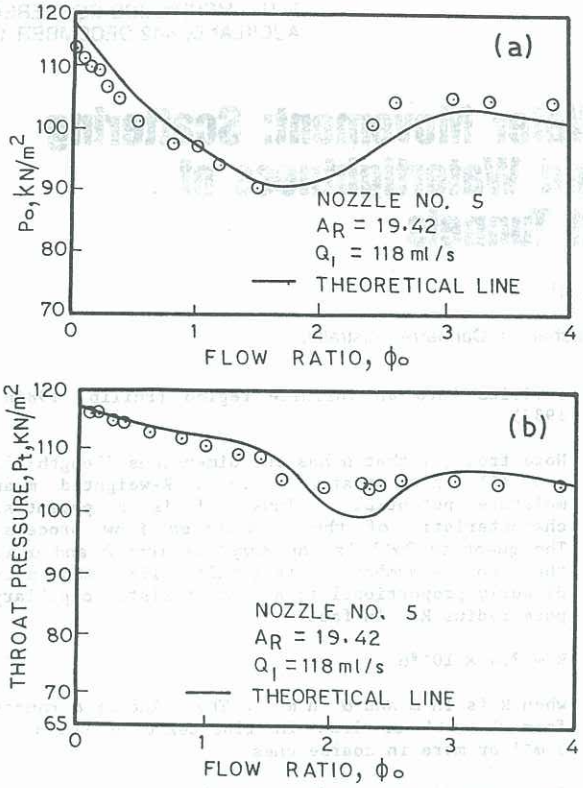

Fig 6 : Model-Experiment Comparison
a) Suction Pressure
b) Discharge Pressure

K_{di} net diffuser coefficient

K_{dif} frictional diffuser loss coefficient

K_{dim} diffuser coefficient due to incomplete momentum transfer

K_{th} net throat coefficient

K_{thf} frictional throat loss coefficient

K_{thm} coefficient due to incomplete momentum transfer in throat.

L_d, L_t length of divergent diffuser and mixing throat respectively, m

m_1, m_2 mass flow rate of water and air respectively, kg/s

$P_o, P_t,$
P_d pressure at o,t,d respectively, N/m^2

Q volumetric flow rate, m^3/s

V linear velocity, m/s

Z height above datum, m

GREEK SYMBOLS

ϕ volumetric air-water flow ratio

ϕ_c departure flow ratio

ϕ_c' flow ratio at which non-homogeniety is maximum

ϕ_h flow ratio at which flooding is removed

ρ density, kg/m^2

γ air-water density ratio

τ frictional wall shear stress, N/m^2

SUBSCRIPTS

1,2,3 water, air and homogeneous mixture respectively

o,t,d position, Ref., Figure 4a

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