Furthermore, for undefined mixtures, such as coal liquids, a method of determining the extent of association is required. The slope of the molecular weight versus concentration curve appears to be a parameter which can be used to characterize this association, although at present the results cannot be used to quantitatively correct for errors in enthalpy correlations.

ACKNOWLEDGMENTS

The authors wish to thank the Office of Fossil Energy, Department of Energy for support of this work, Contract DE-AC22-81PC40787.

NOTATION

g	= grams of solute
G	= grams of solvent
k_f	= constant defined in Eq. 2 (K g/gmol)
l_f	= latent heat of fusion of the solvent (J/g)
M	= apparent molecular weight of the solute (g/gmol)
R	= gas constant (J/gmol·K)
T_f	= freezing-point of the solvent (°R or K)
ΔT_f	= observed depression of the freezing point (K)
α	= molecular weight at infinite dilution (g/gmol)
β	= slope of molecular weight versus solute concentration in benzene [g/gmol/(cc/20cc benzene)]
X	= composition of solute in benzene (cc/20cc solvent)

LITERATURE CITED

American Petroleum Institute (API), "Technical Data Book—Petroleum Refining," 2nd ed., New York (1970).

Auwers, K., "Ueber das Rryoskopische verhalten substituierter phenole in naphtalin," *Z. Physik. Chem.* (*Leipzig*), **18**, 595 (1895).

Beckmann, E., "Uber die methode der molekulargewich-tsbestimmung," *Z. Physik. Chem.*, Leipzig, **2**, 715 (1888).

Beckmann, E., "Bestimmung von molekulargewichten," *Z. Physik. Chem., Leipzig*, **6**, 437 (1890).

Billmeyer, Jr., F. W., *Textbook of Polymer Science*, 2nd ed., Wiley-Interscience, New York (1971).

Chaplin, H. O., "The Associating Effect of the Hydrogen Atom. Part I. Amides and Sulphonamides," *J. Chem. Soc.*, 1114 (1937).

Chaplin, H. O., "The Associating Effect of the Hydrogen Atom. Part II. Substituted Anilides and Related Substances," *J. Chem. Soc.*, 375 (1938).

Chaplin, H. O., "The Associating Effect of the Hydrogen Atom. Part III. Further Examples of Steric Interference between Vicinal Groups," *J. Chem. Soc.*, 1034 (1938).

Chaplin, H. O., and L. Hunter, "The Associating Effect of the Hydrogen Atom. Part IV. Salicyl and Acetocetanilides," *J. Chem. Soc.*, 484 (1939).

Johnson, R. L., and H. G. Grayson, "Enthalpy of Petroleum Fractions," *Petroleum Refiner*, **40**, 2, 123 (1961).

Kesler, M. G., and B. I. Lee, "Improve Prediction of Enthalpy of Fractions," *Hydrocarbons Processing*, **55**, 3, 153 (1976).

Lassettre, E. N., "The Hydrogen Bond and Association," *Chem. Revs.*, **20**, 259 (1937).

Peddle, C. J., and W. E. S. Turner, "Molecular Association in Water," *J. Chem. Soc.*, **99**, 685 (1911).

Sharma, R., "Enthalpy Measurements for a Coal-Derived Naphtha and Middle Distillate and Characterization of Coal-Liquids for Their Extent of Association," Ph.D. Thesis, Colorado School of Mines (1980).

Sharma, R., A. J. Kidnay, and V. F. Yesavage, "The Measurement and Correlation of the Enthalpy of Coal Derived Liquids," *Energy Progress*, **2**(1), 9 (1982).

Shoemaker, D. P., C. W. Garland, and J. I. Steinfeld, *Experiments in Physical Chemistry*, 3rd ed., McGraw-Hill, New York (1974).

Manuscript received September 18, 1981; revision received January 25, and accepted February 22, 1982.

Rise in Free Surface Caused by Submerged Jet Directed Upward

UICHIRO NARUSAWA,
SHINGO TAKAO,
and YUTAKA SUZUKAWA

Technical Research Center,
Nippon Kokan, K.K., Kawasaki, Japan

Because of their importance in many industrial and environmental studies, the areas of research on fluid jets are numerous and diverse. (See Rose, 1956; Martin, 1977; Turner, 1979, for example.) However, we have failed to find any literature concerning the effect of fluid jets on a free surface, resulting in the experimental invesetigation reported here. The ability to predict the surface rise in a fluid due to an impinging jet would certainly contribute to our present understanding of the degree to which the presence of free surface affects a fluid jet, and vice versa.

Figure 1 is a sketch of the present problem, in which d_S and u_S are respectively the average value of effective jet diameter and vertical velocity at the distance H from the jet nozzle in the absence of a free surface. They are related to jet nozzle characteristics, u_o and d_o, by:

$$u_s = u_o(d_o/d_s), \tag{1}$$

$$d_s = d_o + \beta H, \tag{2}$$

where $\beta = 4\,\alpha = 2\tan(\theta/2)$. The entrainment coefficient, α, indicates the ratio of a mean flow velocity across the jet boundary to the mean jet upward velocity. The value of β obtained by previous investigators ranges from ~0.32 to ~0.45 (Folsom and Ferguson, 1949; Donald and Singer, 1959; Ricou and Spalding, 1961; Turner, 1979), and in the discussion to follow, the two values of $\beta = 0.32$ and 0.45 will be employed. It should also be noted that Eq. 2 is valid only when Re_N is greater than ~3,000 (Folsom and Furguson, 1949), a condition which is satisfied for all practical purposes. Then, based on dimensional analysis, the present problem can be expressed in terms of three nondimensional parameters of h/d_o, d_o/d_s and $u_o/\sqrt{gd_o}$ ($\equiv Fr_N$).

The experimental apparatus consisted of an acrylic tank (1.2 m dia. × 1.0 m height), a vertically-directed nozzle and a recirculation lines fitted with a valve, a flowmeter and a pump. The nozzle, made of glass, was placed at the center of the tank bottom. A scale, which could be moved perpendicular to the free surface, was installed above the jet nozzle. At the tip of the scale was attached a

---

Correspondence concerning this paper should be addressed to: S. Takao, Department No. 5, Technical Research Center, Nippon Kokan, K.K., 1-1 Minamiwatarida, Kawasaki-ku, Kawasaki, Japan 210.

0001-1541-83-6340-0511-$2.00.

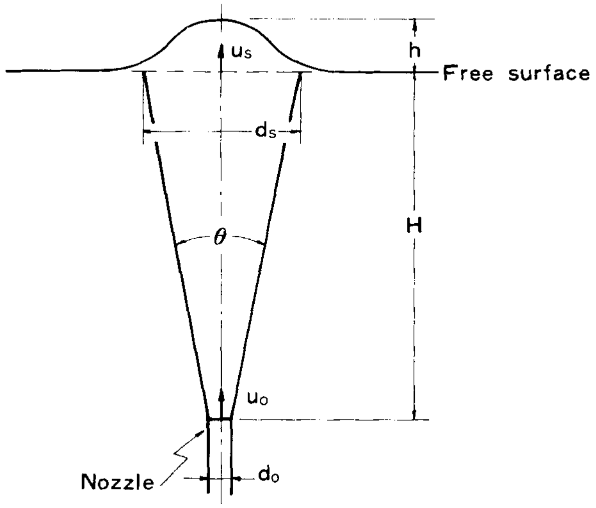

Figure 1. Vertical, free jet impinging on a free surface.

TABLE 1. RANGE OF EXPERIMENT

d_o [mm]	H [cm]	Fr_N	Re_N
0.38	5–15	233	4.7×10^3
1.0	7–30	111	9.5×10^3
4.6	10–25	94.4	8.0×10^4
7.8	1–25	37.8, 25.2, 18.9 13.4, 2.89	$(2.5 \times 10^4) - (7.0 \times 10^4)$
13.4	5–35	6.52, 3.26	$(1.4 \times 10^4) - (2.7 \times 10^4)$

plate, the lower edge of which was very sharp so that by vertically sliding the scale until the tip of the attached plate touches the water surface and reading the change in reference level of the scale, the distance between the water surface and the reference level of the scale could be obtained accurately. A cathetometer was used to locate the point at which the edge of the plate touches water surface.

The test procedure was as follows.

(1) A nozzle with a known diameter was placed in the tank.

(2) The tank was filled with water to a specified depth.

(3) The initial level of the quiescent water surface was obtained from the reading in the vertical tube connected at its bottom to the tank.

(4) The pump was started and the flow rate set to a predetermined value.

(5) After a steady state was reached, the reading for a surface rise was obtained.

(6) Procedures (3) through (5) were repeated. Tests were run for various values of H, u_o and flow rate. Table 1 lists the range of our experiment.

Since the ratio of d_s (calculated from Eq. 2) to the tank diameter was very small ($1/6$ or less), we assumed *a priori* that the effect of the tank wall on our result would be negligible. When a submerged jet impinges on a free surface, surface waves are generated. However, the wave height is very small compared with the value of h (for instance, in our case at $h = \sim 35$ cm, the wave height was less than 1 cm); thus, we concluded that the effect of waves on our experimental results could be regarded as negligible. Fluctuation of the height was found to increase with the height itself, but was less than 5% of the height, h, for all runs. In addition, based on the accuracy of the flowmeter, the velocity of jet at the nozzle was found to be accurate within ±2%.

Figure 2 shows the relationship between h/d_o and $(1 + \beta H/d_o)^{-1}$ with Fr_N as parameter. For $\beta = 0.45$, all the data points are shown with each solid line indicating a least-square fitting for a given value of Fr_N. Since $(1 + \beta H/d_o)^{-1} < 1$ for a submerged jet, the experimental range of $0.006 \leq (1 + \beta H/d_o)^{-1} \leq 0.7$ shown in Figure 3 is quite wide. From Figure 2, it can be seen that h/d_o

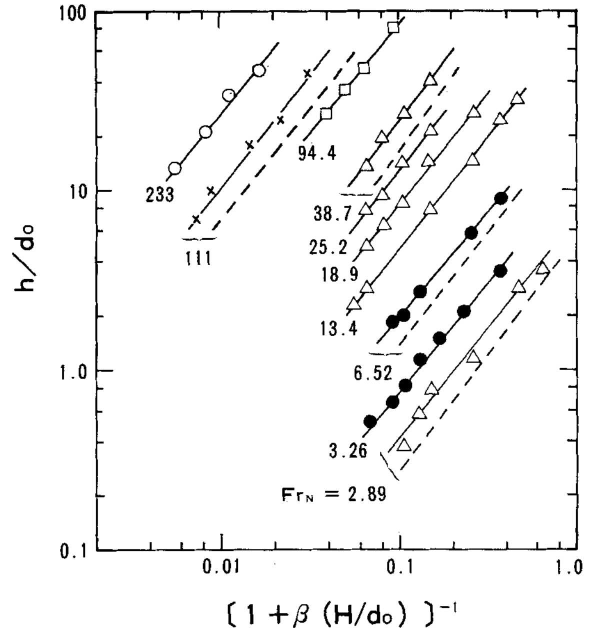

Figure 2. Experimental results: h/d_o vs. $[1 + \beta(H/d_o)]^{-1}$ with Fr_N as parameter. Solid lines are least-square fitted lines for $\beta = 0.45$ and dotted lines for $\beta = 0.32$. All data points are for $\beta = 0.45$. ○: $d_o = 0.38$[mm], ×: $d_o = 1.0$[mm], □: $d_o = 4.6$[mm], △: $d_o = 7.8$[mm], ●: $d_o = 13.4$[mm].

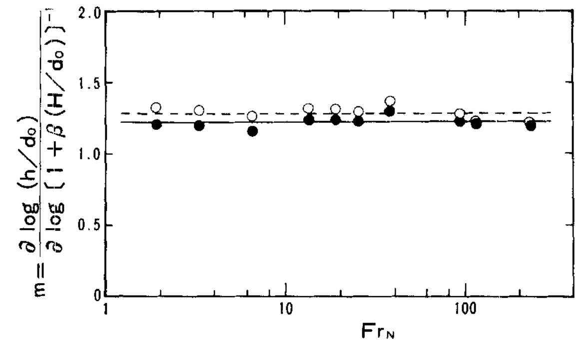

Figure 3. Experimental results: $\partial(\log h/d_o)/\partial(\log[1 + \beta(H/d_o)]^{-1})$ vs. Fr_N. - - - -○- - - -: $\beta = 0.32$, —●—: $\beta = 0.45$.

increases linearly with $(1 + \beta H/d_o)^{-1}$ in a log-log scale, and that any two solid lines appear to be parallel to each other. (This latter point will be demonstrated more clearly in the next figure.) To illustrate the effect of β on the relationship between H/d_o and $(1 + \beta H/d_o) -1$, four least-square fitted lines with $\beta = 0.32$ are shown as dotted lines, indicating the same general tendency described for the case of $\beta = 0.45$.

Figure 3, in which the slopes of the lines are plotted against Fr_N, suggests the following relationship,

$$\log[(h/d_o)(1 + \beta H/d_o)^m] = g(Fr_N), \tag{3}$$

where m is a constant independent of Fr_N, and has a value of 1.22 for $\beta = 0.45$ and 1.29 for $\beta = 0.32$, respectively. To obtain the form of $g(Fr_N)$ in Eq. 3, Figure 4 is plotted (solid line for $\beta = 0.45$, dotted line for $\beta = 0.32$); I indicates the range of $\log[(h/d_o)(1 + \beta H/d_o)^m]$ with $\beta = 0.45$ and $m = 1.22$ for a fixed value of Fr_N. Figure 4 again yielded a linear relationship in a log-log scale, giving the final equation relating the three nondimensional parameters as,

$$h/d_o = A \frac{Fr_N^n}{(1 + \beta H/d_o)^m}, \tag{4}$$

where $A = 1.62$, $m = 1.22$, $n = 1.54$ for $\beta = 0.45$, and $A = 1.25$, $m = 1.29$, $n = 1.56$ for $\beta = 0.32$. Equation 4 indicates that for a given nozzle diameter, d_o, the height of surface rise, h, increases

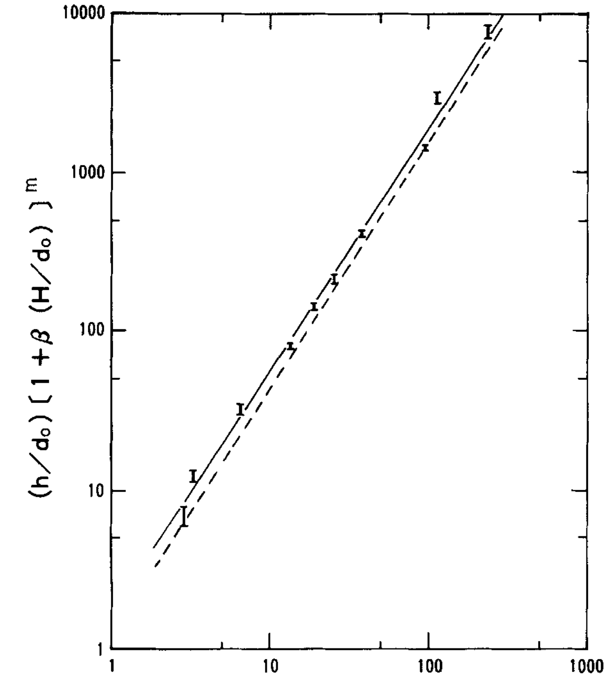

Figure 4. Experimental results: $(h/d_o)[1 + \beta(H/d_o)]^m$ vs. Fr_N. —I—: data point and least-square fitted line for $\beta = 0.45$ and $m = 1.22$. - - - - - - - - -: least-square fitted line for $\beta = 0.32$ and $m = 1.29$.

with the n-th power of the nozzle velocity, u_o, and decreases with the inverse of the m-th power of the effective jet diameter, d_s. The above values determined experimentally for $\beta = 0.45$ and 0.32 indicate that the choice of the entrainment coefficient does not affect our results so sensitively. However, since the calculated value of standard deviation, $(1/N\Sigma_i^N \{(h/d_o)_{\text{measured}}/(h/d_o)_{\text{calculated}}]-1\}_i^2)^{1/2}$, was 0.16 for $\beta = 0.45$ and 0.20 for $\beta = 0.32$, respectively, we concluded that $\beta = 0.45$ was a slightly better choice between the two. We also checked to make certain that the selection and assignment of the value of β between 0.32 and 0.45 did not improve the accuracy of the empirical equation.

In applying the above results, the following care should be taken.

(1) Effect of surface tension is not taken into account, and the liquid used is water only, indicating that further study is needed before the present result can be applied with confidence to liquids other than water.

(2) The present results cannot be applied to the case of two miscible fluids or two immiscible fluids.

NOTATION

A = constant defined in Eq. 4
d_o = nozzle diameter
d_s = jet diameter at the distance H from the nozzle, in the absence of as free surface
Fr_N = Froude number defined as $u_o/\sqrt{gd_o}$
g = gravitational acceleration
h = height of a free surface rise
H = distance between the nozzle and a quiescent free surface
m = constant defined in Eq. 3
n = constant defined in Eq. 4
N = number of data points
Re_N = nozzle Reynolds number defined as $u_o d_o/\nu$
u_o = jet velocity at the nozzle
u_s = average jet velocity at the H from the nozzle, in the absence of a free surface

Greek Letters

α = entrainment coefficient
β = $4\,\alpha = 2\tan\theta/2$
θ = angle of jet spread
ν = kinematic viscosity of liquid

LITERATURE CITED

Donald, M. B., and H. Singer, "Entrainment in turbulent fluid jets," *Trans. Inst. Chem. Engrs.*, 37, 255 (1959).
Folsom, R. G., and C. K. Ferguson, "Jet mixing of two liquids," *Trans. ASME*, 73 (Jan., 1949).
Martin, H., "Heat and mass transfer between impinging gas jets and solid surfaces," *Adv. in Heat Trans.*, ed., T. F. Irvine, Jr., and J. P. Hartnett, 13, 1 (1977).
Ricou, F. P., and D. B. Spalding, "Measurements of entrainment by axisymmetric turbulent jets," *J. Fluid Mech.*, 11, 21 (1961).
Rouse, H., "Seven exploratory studies in hydraulics," *J. Hydr. Div. ASCE* 82, 1038-1 (1956).
Turner, J. S., "Buoyancy Effects in Fluids," Cambridge University Press, 165 (1979).

Manuscript received November 17, and accepted December 2, 1981.

Degree of Segregation and Coalescence Rate Parameter in the Random Coalescence Model for a Stirred Reactor

P. F. MARCONI and N. VATISTAS

Istituto di Chimica Industriale ed Applicata, Università di Pisa, Pisa, Italy

Danckwerts' degree of segregation, J, has been calculated for the random coalescence model as a function of the mixing parameter. J was found to coincide with the intensity of segregation, I_s. It was possible to relate the degree of segregation to the characteristics of the turbulent field within the reactor.

The degree of segregation, J, introduced by Danckwerts (1958) is the usual parameter by which the quality of micromixing has come to be evaluated in the literature of chemical reactors. Actually Rippin (1967) and subsequently other authors (Nishimura and Matsubara, 1970) have demonstrated that giving both the degree of segregation and residence time distribution is, in general, insufficient to identify reactor behavior unequivocally, except for the extreme cases of complete segregation or complete mixing. In other cases, the degree of segregation is only an average parameter of the reactor. It is, nevertheless, usual to compare different models