$$a_{k1} = (i-1)\frac{\beta}{\beta+1}\eta_k + \frac{\beta}{\beta+1}\gamma_k$$
$$a_{k2} = -(i-1)\eta_k - \gamma_k \qquad k = 1, 2, 3 \qquad (A7)$$
$$a_{k3} = j\eta_k$$

$$Y = \begin{bmatrix} Y_{xF}^3 & 0 & 0 \\ 0 & Y_\infty^2 & 0 \\ 0 & 0 & Y_\infty^3 \end{bmatrix} \qquad (A8)$$

where for notational convenience we have used

$$\eta_1 \equiv \mathcal{H}_{xF}^3, \quad \gamma_1 \equiv \mathcal{G}_{xF}^3, \quad F_1 \equiv F_{3,1}$$
$$\eta_k \equiv \mathcal{H}_\infty^k, \quad \gamma_k \equiv \mathcal{G}_\infty^k, \quad k = 2, 3 \qquad (A9)$$

In order to find a nontrivial solution of (A6), we require

$$\det(A - Y) = 0 \qquad (A10)$$

which is the characteristic equation for s. Equation (15) follows from (A7) to (A10) by standard manipulation.

Manuscript received April 10, 1973; revision received and accepted May 17, 1973.

Water Jet Atomization of Molten Steel

Data are obtained and a model derived for describing particle size distribution for molten metals atomized by two water jets. The influences of water jet parameters on size distribution and median size are reported and discussed in terms of fundamental quantities and model predictions. The data, which were obtained using fan-spray jets impinging at an apex angle of 60° to atomize Type 4620 steel, indicated that median size was primarily a function of water jet velocity.

RICHARD J. GRANDZOL
and
JOHN A. TALLMADGE

Department of Chemical Engineering
Drexel University
Philadelphia, Pennsylvania 19104

SCOPE

This paper is concerned with the description of the atomization of molten metals by impinging water jets. This process is a major method for production of metal powders which are used increasingly in manufacture of precision parts by powder metallurgy. The geometry of concern involves a two-liquid system which is more flexible and more suitable for molten metals than the usual one-liquid atomization methods, two of which are use of rotating disk or a pressured nozzle. As compared with isothermal atomization of organic and aqueous liquids, the quench aspect of cooling the molten metal is desirable from an experimental standpoint because the resultant particles are obtained in solid form; this permits simple determination of the size distributions instead of the complex methods needed for fluid droplets.

There is considerable empirical work on the atomization of aqueous and organic liquids by a gas stream, as noted in the summary by Lapple et al. (1967). However, little work on water jet atomization of liquids has been published. Studies by Small and Bruce (1968), Gummeson (1972), and others indicate that the median size and other properties of powders formed by water and gas atomization differ to a large degree; thus it is apparent that the work for gas atomization is not suitable for description of water atomization. Hence an analysis of water atomization of liquid metals would be useful, especially if prediction models are developed and compared with precise data.

The two main objectives of this paper are to describe the median size of metal powders in two ways, experimentally and with a model, using two-jet atomization of molten 4620 steel. As part of this, the influence of several jet parameters was studied in order to determine which ones were primary, secondary, or negligible in their effect on median size and size distribution. The water jet parameters studied included pressure, momentum, energy, velocity, flow rate, and jet length. The influence of metal flow rate was studied by varying the diameter of the molten metal stream. The model approach is based on conservation of momentum and energy balances for the dispersed water droplets, supplemented with data from other measurements.

CONCLUSIONS AND SIGNIFICANCE

Atomization data show that water droplet velocity (V_w) is the fundamental variable influencing median size of the metal particle (d_m). The following functional form was observed (Figure 7), where A is a constant:

$$d_m = A/V_w \qquad (1)$$

Throughout this work, median size refers to the mass median particle diameter (or volume median since density was considered to be constant). Over the ranges studied, it was also found that water pressure, momentum, and energy were not primary parameters influencing median size but did affect size by influencing water jet velocities.

Correspondence concerning this paper should be addressed to J. A. Tallmadge.

This surprisingly simple relationship was not expected and, if valid for more general conditions, would be useful for studying mechanisms and in design. Preliminary tests indicate that the influence of metal flow rate and jet lengths on median size were not appreciable.

The dependence of size distribution on parameters appeared to be even simpler than median size. Over the ranges studied, the distribution of particle size was not influenced appreciably by any of the several parameters studied.

A model of two-liquid atomization was derived, based on two conservation balances for the droplets. Although elementary, the model agrees quite well with the data in functional form; see Equation (1). The model suggests that water jet velocity is the variable of primary importance and that water flow rate per se has no effect on metal particle diameter, both of which agree with observed data.

The model of atomization proposed here appears novel in describing the atomization of one liquid by the dispersed phase of a second liquid. Most atomization models are restricted to cases where the atomizing medium is continuous. The model is described as the impact of a water droplet on the surface of the liquid metal stream, causing metal droplets to be formed.

SYSTEM

The water nozzles and resulting water jets, which were used in this work, are shown diagramatically in Figure 1. The jet spray pattern was a flat spray of droplets, with a fan spray angle β. The droplets were formed at the lip of the nozzle. These jets are called flat, fan jets.

The atomization system of concern here involves two liquid streams, molten metal and water, which flow continuously in the geometry shown in Figure 2. The molten metal stream flows downward in free fall from a circular orifice and the high-pressure water stream is forced through nozzles to form a dispersed phase of water droplets. The water jets strike the metal stream at the apex, from which metal droplets are formed. The metal droplets are cooled by water and the surrounding gas to form solid metal powder. This system is called water atomization in powder metallurgy and herein.

In particular, this work is concerned with the influence of jet parameters on particle size and size distribution. Most of the runs were made with standard Type 4620 steel, which has a listed composition (in weight %) of 1.8 Ni, 0.55 Mn, 0.25 Si, 0.25 Mo, 0.20 C, balance Fe (Smithells, 1967).

PREVIOUS WORK

Most of the earlier studies are empirical description of the influence of jet pressure (pressure upstream of the water jet) on powder size and other powder properties. For example, it is clear that median particle size decreases as the water jet pressure is increased (Small and Bruce 1968; Gummeson, 1972). In order to obtain most of the particles in the desirable size range for compaction, such as below 200 microns, it is necessary to use substantial water pressures in the range of about 10,000 kN/m^2 (that is, 100 atmospheres). In addition, some patents have been issued on jet designs.

EXPERIMENTAL PROGRAM

Water Jets and Supply

As shown in Figure 2, a pair of flat-fan water jets were used in all 14 atomization runs. These jets are also called V jets and descaling jets. The nozzles providing the jets were standard stainless steel nozzles made by Spraying Systems Co. The tip dimensions for a typical nozzle (SS number 3240) was a 3 $\times$ 5 mm elliptic orifice in a 3 $\times$ 17 mm slot, the bottom of which was tapered down to the orifice and slightly curved in cross section. See Figure 1.

The specific characteristics for each of the four sizes of nozzles used are given in Table 1. One nozzle was used initially (SS No. 2520). To avoid studying only pressure effects (in which velocity and flow rate both vary simultaneously), a set of three nozzles was used (3220, 3240, 3260). The set of nozzles provided two novel studies not obtainable with a single nozzle, that is, the effect of velocity at constant flow rate and the effect of flow rate at constant velocity. The fan angle β for these nozzles was 25 and 32 degrees.

The nozzles were threaded to the welded manifold shown in Figure 3. A top view of the jet flow (wtihout atomization) is shown in Figure 4. The manifold provided an apex angle of 60° between the two jet streams and had the flexibility to be used with 1, 3, or 4 jets in future work.

Because the water droplets were formed within 5 mm of the nozzles, the attenuation of droplet velocity in the jet distances studied (60 and 120 mm) is a matter of concern. Impact force data provided by the manufacturer (Anonymous, 1967) indicated only very small changes in velocity (0 to 2%) for large jet distances (from 240 to 480 mm). Thus it is clear that attenuation effects were negligible here.

The nozzle manifold was fed by a large, single-stage, three-cylinder reciprocating pump driven by a 56 KW motor and

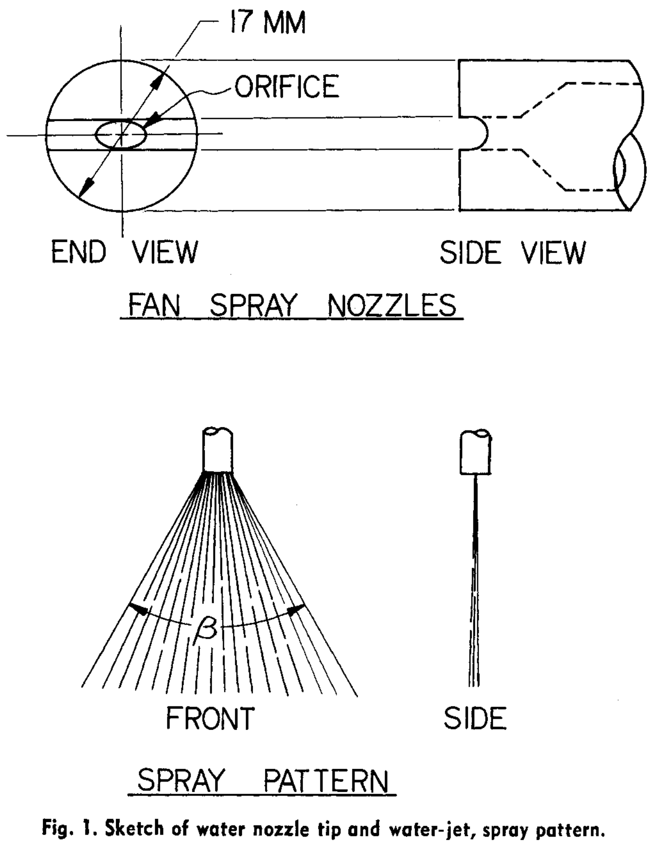

Fig. 1. Sketch of water nozzle tip and water-jet, spray pattern.

capable of delivering 3.8 kg/s water (60 gal./min.) at pressures up to 14,000 kN/m^2 (2000 lb./sq. in.). The water delivery system is shown in Figure 5.

The water flow rate was measured for each run by a rotameter (placed upstream of the recycle line) and was controlled by a flow-control, needle valve (in the recycle line connected to the pump suction). Fluctuations in flow were minimized by use of three cylinders in staggered motion and were further reduced in a 950 cm^3 capacity accumulator placed near the pump discharge.

Metals and Supply

The metal used for most tests was 4620 steel. This is a heat-treatable steel having a solid density of 7.75 g/cm^3 and a melting point of 1516°C (Perry, 1960). The liquid density is about 7.9 g/cm^3.

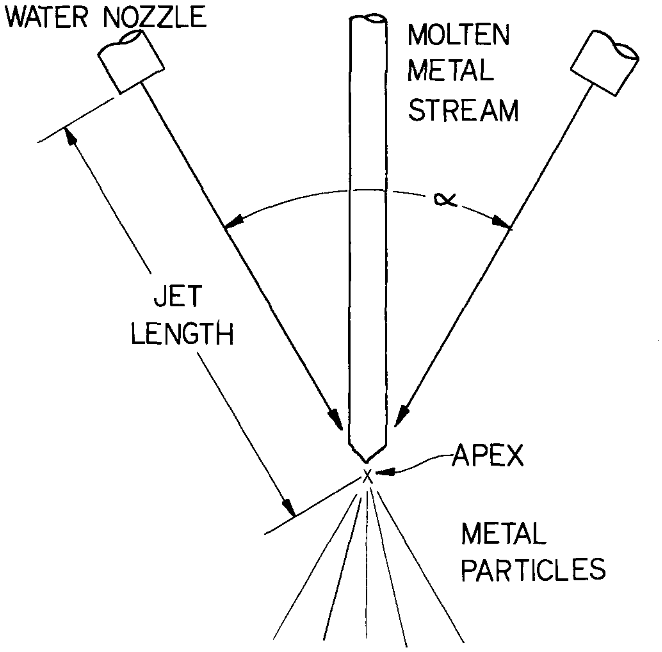

Fig. 2. Sketch of water jet geometry for atomizing molten metals.

The metal stream was provided by flow through the bottom of an insulated tank called a tundish. The tundish was 120-mm inside diameter and 230 mm tall, made of zirconium silicate, and had a fixed, rod-like nozzle at the bottom to restrict the flow. The tundish nozzle used most frequently was 6.4 mm in inside diameter, 26 mm long, and made of zirconium silicate. Two other tundish nozzles, of 4.8 and 8.0-mm diameter, were used to vary metal flow rate.

Batch sizes of about 7 kg were melted in an induction fur-

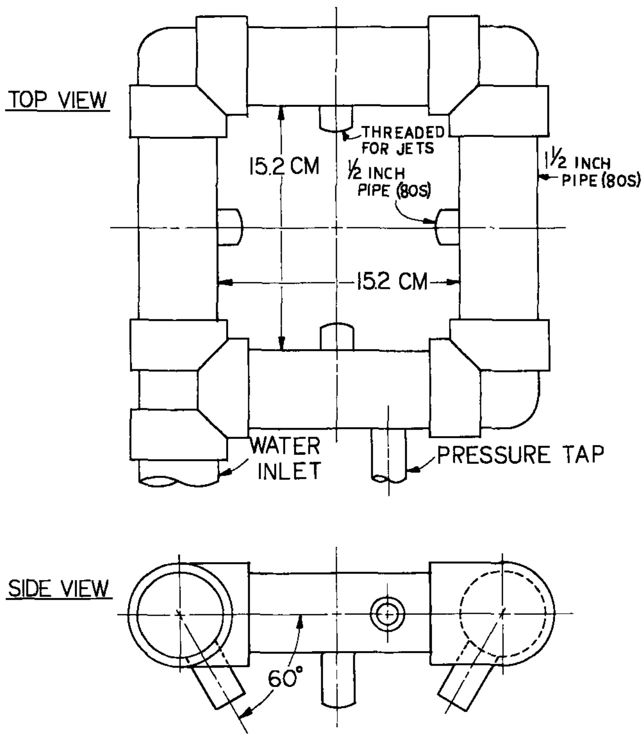

Fig. 3. Manifold for obtaining the desired jet geometry in water-jet atomization—drawn to scale. Material is welded stainless steel.

TABLE 1. CHARACTERISTICS OF THE WATER NOZZLES USED

Nozzle number (a) (spraying systems Code)	25-20	32-20	32-40	32-60
Rated fan angle β (b)	25°	32°	32°	32°
Rated water flow rate (c) (For two nozzles at 6,900 kN/m^2)				
gal/min (b)	20	20	40	60
kg/s	1.26	1.26	2.52	3.78
Orifice dimensions (approx.)				
Short axis, Figure 1, mm	2	2	3	4
Long axis, Figure 1, mm	3.5	4	5	6.5
Equivalent diameter				
in. (b)	7/64	7/64	5/32	3/16
mm	3.3	3.3	4.7	5.7
Slot dimensions (Figure 1)				
Length, mm	17	17	17	17
Width, mm	2	2	3	4
Water velocity, m/s (d) (At 6,900 kN/m^2)	107	107	107	107
No. of atomization runs (This work)	5	2	4	3

(a) Code. The first two digits of this four-digit, Spraying Systems code refer to the fan angle β (in degrees) and the last two digits refer to the rated flow rate (in gal/min) for a pair of nozzles at the reference pressure of 1000 lb./sq.in.gauge (6,900 kN/m^2).

(b) Data Source. Supplied by the manufacturer (Anonymous 1967) for these nozzles of the H-⅜-UHSS-E Series. Dimensions, capacities and impact data are also listed by Grandzol (1973).

(c) Flow rates. For reference purposes. In this work, flow rate was measured by a rotometer.

(d) Velocity. Calculated from impact data (Anonymous, 1967). Using this impact data, Grandzol (1973) has shown that the water jet velocity V_w, in m/s, is described for all four nozzles by

$$V_w = 1.3\,P^{1/2}$$

where P is the pressure in kN/m^2.

nace, poured into the tundish, and allowed to flow into a 1.3-m diam., 1.5-m high chamber for atomizing and quenching. The furnace used in melting the metal and the atomization chamber used in this work have been described previously for gas atomization. Chamber details are given in Rao et al. (1971), Rao and Tallmadge (1972), and Rao (1973); furnace details are given in Rao (1971).

Operating Conditions

The directly measured conditions were water flow rate, water pressure, metal temperature, metal batch size, and duration of the total metal flow time. From these experimental quantities, metal flow rate, water velocity, energy, and momentum were calculated. The experimental conditions for the runs appear in Tables 2 and 3. It is seen that the range of variables studied is as follows: water kinetic energy (12×), water momentum (8×), water pressure (8×), water flow rate (5×), water velocity (3×), and metal flow rate (3×).

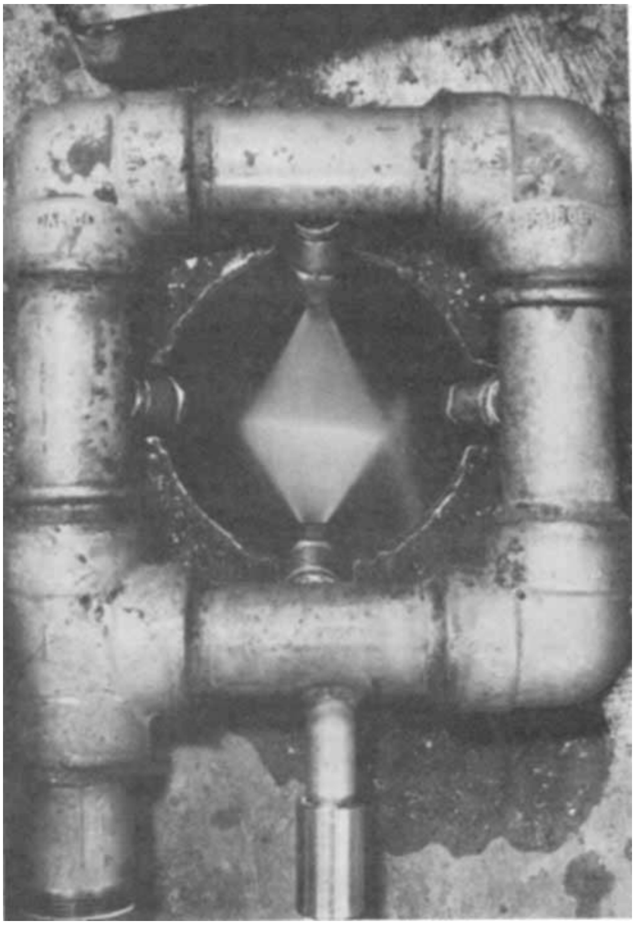

Fig. 4. Photograph of water sprays without atomization—top view of manifold with tundish removed. Nozzle No. 2520. Pressure of 3500 kN/m^2. (500 lb./sq.in.).

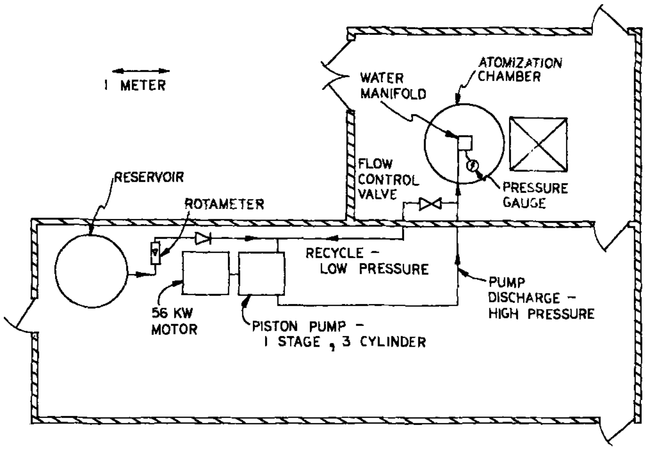

Fig. 5. Water pump and supply system—drawn to scale. Floor plan of water-jet atomizing unit.

TABLE 2. EXPERIMENTAL CONDITIONS AND RESULTS (LOWER VELOCITY)

Water velocity V_w, m/s	50	50	67	78	78	80	80
Run number	87N	88N	73N	46N	70N	44N	58N*
Metal Measurement							
Temperature, °C	1,740	1,680	1,760	1,650	1,750	1,720	1,700
Batch size, kg	7.7	7.7	7.7	5.5	7.7	5.5	7.7
Run time, s	34	22	35	40	57	22	32
Metal Conditions							
Tundish nozzle, ID, mm	6.4	8.0	6.4	4.8	4.8	6.4	6.4
Flow rate, W_m, kg/s	0.23	0.35	0.22	0.14	0.14	0.25	0.24
Water Measurement							
Nozzle number	3,260	3,260	2,520	3,240	3,240	2,520	2,520*
Pressure, kN/m^2	1,600	1,600	2,100	3,500	3,500	3,800	3,800
Flow rate, W_w, kg/s	1.79	1.79	0.76	1.79	1.80	0.91	0.91
Water Conditions							
Momentum rate, kg · m/s^2	90	90	51	142	142	72	72
Kinetic energy rate (Joules, kg · m^2/s^3)	2,200	2,200	1,700	5,600	5,600	2,800	2,800
Screen Analysis, wt. %							
% yield (−60)	73	65	64	96	92	94	82
−60 + 100 (250μ)	35.9	43.0	41.0	14.4	19.7	13.1	16.1
−100 + 140 (149μ)	22.4	22.2	17.9	10.6	15.9	14.8	15.1
−140 + 200 (105μ)	15.7	15.6	13.2	16.0	15.2	17.7	16.9
−200 + 230 (74μ)	4.2	3.7	3.4	4.5	4.5	5.0	5.1
−230 + 325 (63μ)	12.0	9.5	12.3	19.3	17.7	17.7	17.3
−325 (44μ)	9.8	6.0	12.2	35.2	27.0	31.6	29.6
Powder Properties (−60)							
Median size, d_m, μ	117	133	123	61	74	64	67
Diam. ratio, σ	2.10	2.02	2.49	2.33	2.24	2.14	2.24
Coeff. var., C_v	0.33	0.31	0.41	0.38	0.36	0.34	0.36

(*) *Shorter jet length of 60 mm, whereas all other runs were done with a jet length of 120 mm.*

TABLE 3. EXPERIMENTAL CONDITIONS AND RESULTS (HIGHER VELOCITY)

Water velocity, V_w, m/s	107	107	107	107	113	149	149
Run number	38N	69N	37N	45N	60N	61N	40N
Metal Measurement							
Temperature, °C	—	1,700	—	1,680	1,690	1,730	1,690
Batch size, kg	7.7	7.7	7.7	5.5	7.7	7.7	7.7
Run time, s	20	37	35	30	36	58	22
Metal Conditions							
Tundish nozzle, ID, mm	8.0	6.4	6.4	6.4	6.4	4.8	6.4
Flow rate, W_m, kg/s	0.39	0.21	0.22	0.18	0.21	0.13	0.28
Water Measurement							
Nozzle number	2,520	3,240	3,240	3,260	3,220	3,220	2,520
Pressure, kN/m²	6,900	6,900	6,900	6,900	6,900	13,800	13,800
Flow rate, W_w, kg/s	1.26	2.49	2.52	3.78	1.32	1.78	1.79
Water Condition							
Momentum rate, kg · m/s²	134	265	274	303	149	265	268
Kinetic energy rate [Joules (kg · m²/s³)]	7,200	14,200	14,400	21,600	8,400	19,700	20,000
Screen Analysis (wt %)							
% Yield (−60)	71	96	89	93	93	96	69
−60 + 100 (250μ)	10.0	5.4	12.2	6.7	12.4	5.1	5.4
−100 + 140 (149μ)	8.6	8.3	11.7	7.7	12.5	7.3	8.3
−140 + 200 (105μ)	12.2	11.5	15.5	12.9	14.5	11.1	11.5
−200 + 230 (74μ)	4.0	4.9	4.6	4.1	4.2	3.8	3.9
−230 + 325 (63μ)	17.5	18.0	17.5	19.8	16.1	16.7	18.0
−325 (44μ)	47.5	52.9	38.5	48.8	40.3	56.0	52.9
Powder Properties (−60)							
Median size, d_m, μ	47	43	55	46	56	42	30
Diam. ratio, σ	2.46	2.24	2.36	2.18	2.38	2.15	2.76
Coeff. var., C_v	0.41	0.36	0.39	0.35	0.39	0.34	0.46

The molten metal temperatures were measured by immersing a platinum-rhodium thermocouple in the tundish. It is seen that temperatures were held approximately constant near 1710°C, usually within ± 20°C. See Tables 2 and 3.

Pressure characteristics of the fan jets provided by the manufacturer indicated the influence on volume flow rate and impact force. The impact data also showed that jet velocity is constant with distance from the orifice in the operating ranges used here. Using these data, desired values of velocity and flow rate were selected by choosing the proper nozzle and pressure; the flow rate was obtained in a given run by controlling the recycle flow rate.

Metal Particles (Powders)

After atomization, the wet powders were collected, washed with acetone, and dried. Using U.S. Standard number 60 and 100 sieves, a 400-g sample was separated; a 100-g sample of the − 100 mesh portion was then sieved using the standard ASTM test procedure B-214-56.

Most of the powders were smaller than 100 mesh (~ 149μ). The few large particles (~ 2,000μ) observed probably resulted from metal which was seen to splash out of the atomization zone. To eliminate these large particles, each sample was topped and a yield calculated. Instead of using the 100 mesh used commercially, topping was done with a 60 mesh screen to obtain a more representative sample. As shown in Tables 2 and 3, most yields were 89% or above. Thus topping (yield) effects were small at all velocities, except for the three runs at 50 and 67 m/s (Table 2). The two lower yields at higher velocities (Table 3) may have been due, in part, to inexact centering of the metal stream relative to the jet apex.

EXPERIMENTAL RESULTS

Size Distribution

The topped powder for each run was split into the following six fractions using U.S. Standard sieve sizes: − 60 + 100, − 100 + 140, − 140 + 200, − 200 + 230, − 230 + 325, and − 325. The resultant sieve analyses of the powders was then plotted on log normal-probability coordinates. Figure 6 shows, for the velocity sequence of runs 87N, 46N, and 61N, that the sieve size data are linear on this plot. Similar results were observed for other runs. Thus the size distribution for these water atomization runs is a log normal distribution, even though the shape of the metal powders is somewhat nonuniform. This log normal distribution is consistent with earlier gas atomization results of Rao et al. (1970) and others.

Where the size distribution is log-normal, the spread of the size data may be expressed as the slope of the data. This slope may be expressed as the diameter ratio σ given by Randolph and Larson (1971) as the geometric standard deviation:

$$\sigma \equiv \frac{d(0.841)}{d(0.500)} \equiv \frac{d(0.500)}{d(0.159)} \tag{2}$$

This diameter ratio may also be expressed in normalized form as the coefficient of variation C_v given by Randolph and Larson (1971) as

$$C_v \equiv [\exp(\log^2\sigma) - 1]^{1/2} \tag{3}$$

The size distribution of the powders has been characterized by means of both the diameter ratio and the coefficient of variation. Typical values for several sequences of runs, presented in Table 4, show that the size distribution did not vary appreciably with water velocity, water flow rate, or metal flow rate over the ranges studied. Furthermore, it appears that the slope (or spread) for all runs was approximately constant at a diameter ratio σ of about 2.24 and a coefficient of variation, C_v of about 0.36. Individual values vary about ± 8%, which is within experimental error.

It is concluded, therefore, that the spread of size distribution may be considered to be constant for the conditions studied. This is an important simplification, which allows description of size data using a single parameter, such as median size. In this paper, the mass median size d_m is taken from the cumulative weight plot as the diameter of the particle for a cumulative weight of 50%. See Figure 6.

Repeatability

Several duplicate runs were performed to test the reproducibility of the experimental technique. Most results agreed closely. In one case the median particle size for the repeat run (117μ for 87N) differed substantially from the first run (51μ for 47N). After comparison with other runs (73N, 88N) at similar conditions, run 47N was believed to be in error and was dropped.

Reproducibility results for the other pairs of runs are given in Table 5, both in terms of parameters which are difficult to control precisely (metal temperature and flow rate) and in terms of the resultant powder properties. Table 5 shows that deviations from average values were small. These deviations represent large reductions (factors of 3× to 10×) in the deviations observed in the initial, exploratory runs. In view of the difficulty of controlling hot metal conditions in short runs, the deviations in Table 5 are considered to be satisfactory.

MEDIAN SIZE DATA

Tests with different nozzles were utilized to study the influences of water velocity at a constant water flow rate (1.79 kg/s) and the influence of water flow rate at constant velocity (107 m/s). See Table 4. These and other tests (Tables 2 and 3) provided for independent study of the effect of four water-jet parameters, namely velocity, flow rate, momentum, and kinetic energy. Pressure is related to velocity. Impact force is related to momentum.

Plots of the median size data (for all 14 runs) versus each of the four parameters indicated substantial scatter with mass flow rate (W_w), a good correlation with velocity (V_w), and intermediate scatter with momentum ($W_w V_w$) and kinetic energy ($W_w V_w^2/2$).

The size versus flow rate scatter was due to negligible effect of flowrate on size, which was observed. At $V_w = 107$ m/s, for example, Table 3 shows that size is constant at about $49 \pm 5\mu$ for 5 runs in which flow rate was varied threefold. Table 2 shows confirmation of the constancy of size with a two-fold variation in flow rate at 80 m/s ($d_m = 67 \pm 4\mu$ for 4 runs) and near 58 m/s ($d_m = 124 \pm 6\mu$ for 3 runs). It was concluded that size is independent of flow rate per se, over the ranges studied.

Figure 7 shows the influence of velocity for all 14 runs. The major trend apparent here is that the median particle size is inversely proportional to water droplet velocity, or

$$d_m = 5{,}500/V_w \quad (4)$$

Equally important is the fact that the scatter is small and within experimental error, even though there is a wide variation in water flow rate. Equation (4) is the basis for Equation (1). It was concluded that velocity was the best parameter for correlating median size.

Plots of other variables indicated scatter. To illustrate this, Figure 8 shows a similar graph of all size data plotted versus momentum ($W_v V_w$). A general trend of size decreasing with increasing momentum is given as the solid line, although scatter is appreciable. On the other hand, sets of data taken at constant velocity (dotted lines) indicate that median size was *not* a function of jet stream momentum; this independence is inconsistent with the general trend of the momentum plot. Thus, it appears that atomization was due mainly to a droplet effect and that water momentum (per se) did not influence particle size. A similar plot and argument applies to water kinetic energy ($W_v V_w^2/2$), but the scatter is less than with momentum, probably because the square of velocity dominates the influence of flow rate.

A plot of size versus pressure was similar in scatter to the velocity plot and indicated that size was inversely proportional to the 0.5 or 0.6 power of pressure. The square root effect is consistent with the velocity effect of

TABLE 4. SIZE DISTRIBUTION DATA

Independent variable Parameter	Meas. value	Diameter ratio σ	Coefficient of variation C_v	Run number
Water	50 m/s	2.10	0.33	87N
Jet	78 m/s	2.33	0.38	46N
Velocity (a)	149 m/s	2.15	0.34	61N
Water	1.32 kg/s	2.38	0.39	60N
Jet	2.49 kg/s	2.24	0.36	69N
Flow rate (b)	3.78 kg/s	2.18	0.35	45N
Metal	0.21 kg/s	2.38	0.39	60N
Flow rate	0.23 kg/s	2.10	0.33	87N
	0.35 kg/s	2.02	0.31	88N
	0.39 kg/s	2.46	0.41	38N
Other runs		2.36	0.39	37N
		2.76	0.46	40N
		2.14	0.34	44N
		2.24	0.36	58N
		2.24	0.36	70N
		2.49	0.41	73N
Median		2.24	0.36	
Average deviation from median		±0.14 (6%)	±0.03 (8%)	

(a) At constant water jet flowrate of 1.79 kg/s.
(b) At constant water jet velocity of 107 m/s.

TABLE 5. REPRODUCIBILITY

Atomization variables	First test Run 46N	Run 70N	% dev. (a)	Second test Run 37N	Run 69N	% dev. (a)
Preset condition						
Water pressure, (b), kN/m²	3,500	3,500	—	6,900	6,900	—
Measured cond.						
Metal temp., °C	1,650	1,750	±3	unk.	1,680	unk.
Metal flow, kg/s	0.14	0.14	negl.	0.22	0.21	±2
Powder properties						
Mean size, μ	61	74	±10	55	43	±12
Size dist., σ	0.38	0.36	±3	0.39	0.36	±4
% yield (−60)	96	92	±2	89	96	±4

(a) % deviation from the mean.
(b) Nozzle number 3240.

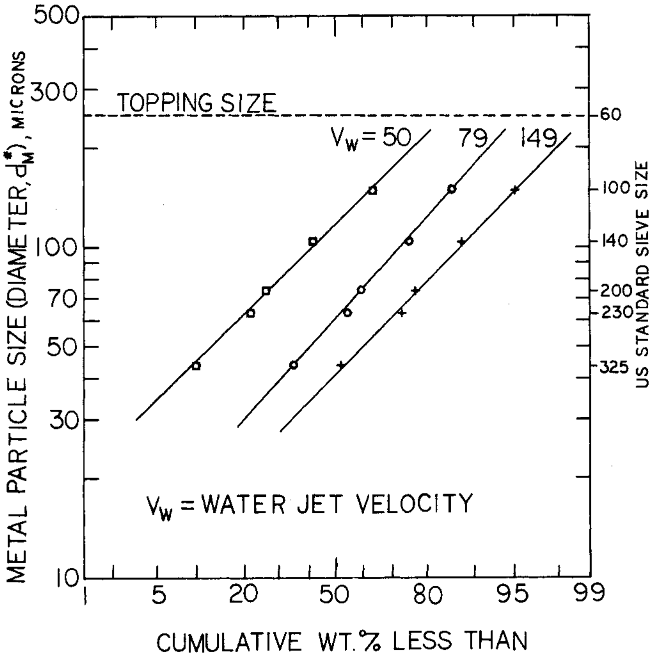

Fig. 6. Effect of water jet velocity on metal size distribution: cumulative plot of screen size data. 50 *m/s* is equivalent to 160 ft/sec.

Equation (4) when the relation between velocity and pressure is considered. The relationship is given in the velocity footnote of Table 1. It is true that pressure is a parameter which is easy to measure and control and thus is useful industrially. However, pressure does not appear to be a fundamental variable because it described the water condition upstream of the water nozzle rather than of the water droplets at the apex.

One reason that velocity is so important may be due to different influences felt at the metal apex (that is, point of contact). For example: changes in droplet velocity probably cause large changes at the apex. However, changes in total mass flow rate (and other variables) may not cause large changes at the apex because of dissipation around the apex. Since only part of the water spray contacts the metal stream, the mass flux at the apex may be a factor.

The conclusion of major dependence on velocity is an important new concept in powder metallurgy because pressure was reported in Small and Bruce (1968), Gummeson (1972), and in most other studies. However, pressure does not appear to be a fundamental variable for describing atomization mechanisms. For example, when pressure is increased for a given jet size, both water velocity and water flow rate are increased.

No appreciable influence of metal flow rate was observed, as indicated by size data to 50 m/s (117, 133μ), at 79 m/s (64, 67, 61, 74μ), and at 107 m/s (47, 43, 55, 46μ). However, water flow rate was also varied in these runs so that interactions may be present. Variations in metal temperature may also have contributed to scatter in the size data. No systematic influence was noted, however, probably because the temperature variations have been kept to a small range (Table 1).

Another variable, jet length, was studied at constant velocity (79 m/s) and constant water flow (0.91 kg/s). Here jet length is the distance along the water jet path from the jet orifice to the water-metal apex point. Although jet length was reduced from the normal length of 120 mm (Run 44N) to 60 mm (Run 58N), the median sizes were nearly identical (64 and 57 microns, respectively) and the powders were virtually indistinguishable. These data also confirm the manufacturer's data that jet velocity is independent of jet length and that droplet velocity is an important and fundamental parameter in water atomization.

In summary, it appears that median size is a function primarily of water jet velocity and that the size distribution is approximately constant for the conditions studied here.

MEAN SIZE MODEL

The objective of this section is to develop a model for water jet atomization of molten metal which is capable of predicting metal particle sizes. In gas atomization of liquid metals (Small and Bruce, 1968; Rao et al., 1971), the metal is impacted by a high-velocity, but continuous gas phase. However, the case of water atomization of liquid metals is different because the water jet is not a continuous phase, but a disperse phase. In other words, the water stream that contacts the metal stream is a spray of water droplets.

A model of atomization by droplets is given below, based on (1) conservation of momentum, (2) literature on water droplet size, (3) velocity data obtained photographically, and (4) conservation of energy.

First, consider that a single water droplet impacts the surface of the metal stream and causes n number of metal drops to be formed. For simplicity, assume that the water droplet transfers all its momentum M_w to the newly formed metal droplets, each of momentum M_m. For this the momentum balance yields

$$nM_m = M_w \tag{5}$$

Here the subscripts m and w refer to metal and water respectively. Writing momentum in terms of an individual, spherical particle diameter d^*, velocity V, and density ρ leads to a relationship between droplet sizes; thus upon rearranging, Equation (5) becomes

$$d_m{}^* = \left(\frac{V_w\,\rho_w}{nV_m\,\rho_m} \right)^{1/3} d_w{}^* \tag{6}$$

Working with median diameters leads to

$$d_m = \left(\frac{V_w\,\rho_w}{nV_m\,\rho_m} \right)^{1/3} d_w \tag{7}$$

Equation (7) predicts metal size as a function of two unknown parameters, water droplet size d_w and metal velocity V_m.

Second, consider the prediction of water droplet size d_w. This is a case of pressure (or hydraulic) atomization for a flat, fan spray. For the liquid sheet (of thickness s and surface tension γ) from the orifice of a flat, fan spray, Straus (1949) and Fraser and Eisenklam (1956) have reported that water droplet size is given by

$$d_w = \frac{C}{V_w} (s\gamma)^{1/3} \tag{8}$$

Straus reported a value for the C parameter which is equivalent to C = 4,860 in the units given in the notation. Fraser and Eisenklam mention the empirical determination of the C parameter for wide-angle, fan jets of β near 110°.

As noted previously, visual and photographic observations indicated that, for the nozzles used here, breakup occurred very close (within 5 mm) to the nozzle orifice. In addition, the water jet velocity calculated from the manufacturer's impact data was very close (within 10%) to the theoretical orifice velocity. These two observations suggested that the thickness of the liquid sheet at breakup is the same as the thickness at the orifice. Since the orifice thickness s and liquid-gas surface tension γ are known, Equation (8) becomes

$$d_w = \frac{B}{V_w} \tag{9}$$

Reported exponents on velocity have ranged from $-2/3$ to -1, but for reasons mentioned in the discussion section below, Equation (9) is used here.

We are now concerned with evaluating the parameter B at the high velocities (> 50 m/s) used here. However, no droplet data for fanjets of this type was available at these high velocities.

Davies (1972) indicates that the droplet diameter has been found to be nearly independent of nozzle size or shape for velocities greater than 25 m/s, which is the case here. Furthermore, Merrington and Richardson (1947) have presented a correlation for high velocities (up to 250 m/s); their equation for droplet size of aqueous and organic liquids issuing from a cylindrical jet is

$$d_w = \frac{3100}{V_w}\left(\frac{\eta}{\rho}\right)^{0.8}_{\text{Gas}}\left(\frac{\eta}{\rho}\right)^{0.2}_{\text{Liq.}} \tag{10}$$

Equation (10) is identical in form to Equation (9). Using properties of air and water of concern in the water jet, the Merrington-Richardson expression predicts that the B parameter of Equation (9) has the value of

$$B = 20{,}000 \tag{11}$$

Since the B parameter was evaluated at high velocities and since velocity is considered to be the dominant variable, Equations (9) and (11) will be used to describe the jets used here. A more detailed analysis may be found in Grandzol (1973). Substituting water nozzle Equations (9) and (11) into momentum Equation (7) leads to an improved prediction of metal particle size:

$$d_m = \left(\frac{V_w \rho_w}{nV_m \rho_m}\right)^{1/3}\left(\frac{B}{V_w}\right) = \left(\frac{V_w \rho_w}{nV_m \rho_m}\right)^{1/3}\left(\frac{20{,}000}{V_w}\right) \tag{12}$$

Third, metal velocity V_m must be evaluated. This was done by taking a high-speed, infrared photograph of the atomization process (Run 87N) and estimating particle velocities from observed trajectory lengths. Results indicated that particle velocities were approximately independent of particle diameter. For this run, the metal particle velocity was found to be 15.3 m/s, whereas the water jet velocity was 50 m/s. Because a kinetic energy balance suggested that the ratio of water droplet velocity to metal particle velocity is the same for all velocities, the ratio was taken to be constant. This constant was evaluated from photographic data to be

$$\frac{V_w}{V_m} = \frac{50}{15.3} \tag{13}$$

Substituting the expression for velocity ratio, Equation (13), into that for metal size, Equation (12), and evaluating densities for both materials leads to the desired model prediction of metal particle size which is

$$d_m = \frac{A}{V_w} = \frac{14{,}900}{V_w}\left(\frac{1}{n}\right)^{1/3} \tag{14}$$

If we assume, as a special case, that $n = 1$ or that one metal droplet is formed for each impinging water droplet, then Equation (14) becomes

$$d_m = \frac{14{,}900}{V_w} \tag{15}$$

Comparison with Data

The comparison of the model, Equation (14), with the metal-size data correlation, Equation (4), is done here in two parts—first in functional form and then in magnitude.

Comparing the form of these two equations, it is seen that the model predicts the inverse, first-power dependence on water velocity observed with data. Thus the model properly predicts the same functional form as that observed experimentally. In addition, the model agrees with the experimental evidence that the direct influence of water flow rate is negligible here. (The basis for the flow rate part of the model is Equations (9) to (11) taken at constant velocity).

Since the model has one adjustable parameter n, the ratio of metal particles to water impacts, comparison with data can be made in two ways. One way is to choose n. For $n = 1$, the model predicts median sizes ($A = 14{,}900$) which are 3× as large as data ($A = 5{,}500$); or for $n = 10$, $A = 6{,}900$. On the other hand, using data as the reference, the model suggests an average of $n = 20$. We conclude that the model predicts the proper order of magnitude of median metal size. In summary, the model was based on:

1. A momentum exchange equation for size,
2. Use of literature correlations for water droplet size as a function of water jet velocity,
3. A kinetic energy exchange equation for the velocity ratio, and
4. Use of a photographic determination of metal particle velocity.

The model was found to be surprisingly useful in predicting the functional form for the median size correlation.

DISCUSSION OF THE MODEL

The model is tentative because it has some important limitations. For example, the model does not specifically describe any mechanism for the primary breakup of the metal stream although a splash type mechanism is implied (Grandzol, 1973). Furthermore, the relationship between the number of water droplets and the number of metal particles is not available. Of course, the model does not take into account the possibility of two other mechanisms, namely, secondary breakup and coalescence. In this work photographs of the powder indicated some evidence of coalescence of fine metal particles to form larger ones; thus coalescence may have some importance here. It is difficult to determine if secondary breakup occurs at the conditions studied, but this may also play a role. Because of the importance of these aspects, further study of mechanisms is recommended. An alternative mechanism for primary breakup is one involving a wave-ligament formation step (Grandzol, 1973).

The independence of metal size on mass flow rate of water (at constant water velocity) suggests that most of water in the jet is wasted with regard to size; on the other hand, water flow rate is probably important for quenching rate and particle shape. In regard to flow rate, consideration was given to a model in which metal particle size was based on the total number of droplets impacting the metal stream. However, this model was not consistent with experimental flow rate data. For example, water flow rate was varied threefold (at constant velocity, in runs 33N and 45N) with virtually no difference in the resultant particle size. If size was influenced by number per se, tripling the flow rate, which triples the number of droplets, should result in change in particle size, but none was observed. It thus appears that pressure effects are due to jet velocity changes, not to the flow rate changes that occur.

DISCUSSION OF EQUATION (9)

The water droplet equation used in the model was Equation (9), developed for pressure atomization of a liquid into a gaseous chamber.

First, let us consider the exponent on velocity. In effect, Equation (9) implies that median droplet size is proportional to the − 0.5 power of pressure. Some authors, such as Fraser, Eisenklam, and Dombrowski (1957), show a − 1/3 exponent on pressure (thus − 2/3 on velocity); however, their studies were done at lower velocities where both the sheet thickness s and the jet velocity V_w may attenuate appreciably in the distances considered. On the other hand, velocity to about the − 1 power has been reported or implied by several authors including (1) the fan spray manufacturer (Anonymous 1967), based on square root of pressure; (2) the − 1.06 power of Kruse, Hess, and Ludvik (1949) for fan sprays from airplanes, if their air speed is included in V_w; (3) the − 1.06 power of Radcliffe (1954) for swirl nozzles, based on the − 0.53 power on pressure and the suggestion of Tate (1965) that variation of size with pressure for fan sprays was similar to swirl nozzles; and (4) the − 1.0 power for cylindrical, high pressure jets by Tanasawa and Toyoda (1955), as well as by Merrington and Richardson (1947).

Thus there is substantial evidence to support the use of the − 1 exponent on velocity.

Second, let us consider the magnitude of droplet size produced at given conditions. There is much less agreement on the size of the magnitude parameter B in Equation (9), however. Literature expressions vary by a factor of about 100 in magnitude as illustrated by the calculated B values of 800 from Kruse et al. (1949), 14,000 from Radcliffe (1954), 20,000 from Merrington and Richardson (1947), and 72,000 from Straus (1949). The value used in the model here was chosen using the velocity range studied.

Numerical agreement between the model and the data depends considerably on the literature correlation selected for the water droplet size. Thus good agreement may be fortuitous and poor agreement may be misleading. It is clear that the uncertainty in droplet size would be reduced considerably by having a size characterization of the nozbles actually used, but such was not available here.

Third, although velocity distribution was not used in the model of this work, it has been reported to be quite flat by Eisenklam (1961) and by Dombrowski and Hooper (1962). Thus it appears that in spite of the size distribution (of water droplets in each water spray), most of droplets had a velocity which was nearly constant with size.

DISCUSSION OF DATA

Because yields were 89% or above for most runs (Tables 2 and 3) and because most low yield runs were part of a high-yield group at each velocity, it is believed the topping process had little or no influence on the correlation given in Figure 7 or as Equation (4). The only group of runs with each at lower yield was a group of three at low velocity (50 to 67 m/s); modifying these runs for untopped median size would give slightly larger d_m values for these runs but would not change the overall correlation appreciably. In summary, it is felt that the effect of topping was minor or negligible.

In several studies of pneumatic atomization using air and liquids, the ratio of mass flow rates was found to have an influence on median size. No such effect of metal to water flow rate was found here within the ranges studied, but that was probably due in part to the small

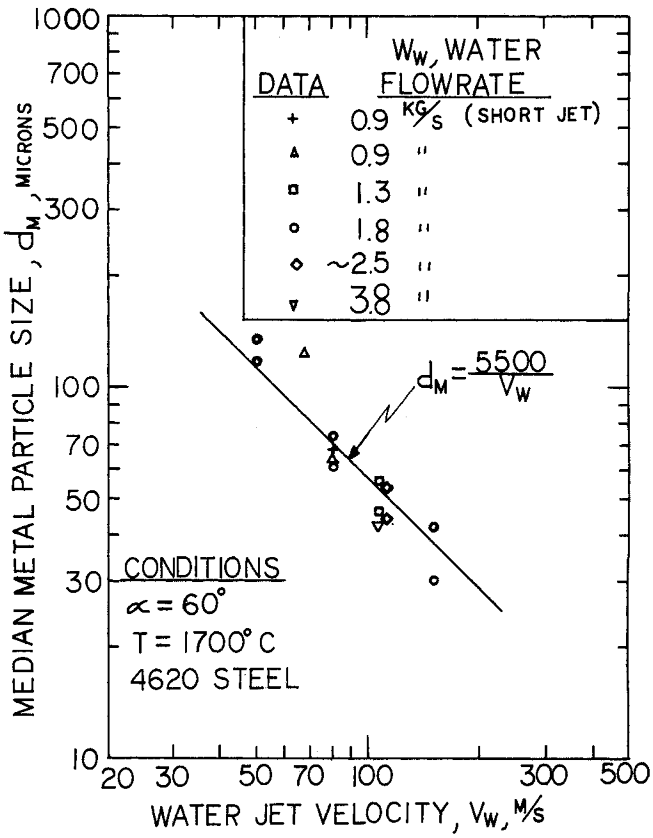

Fig. 7. Effect of water jet velocity and water mass-flow rate on metal size: jet length of 120 mm, except for one short jet run at 60 mm; 0.9 kg/s is equivalent to 14 gal/min.

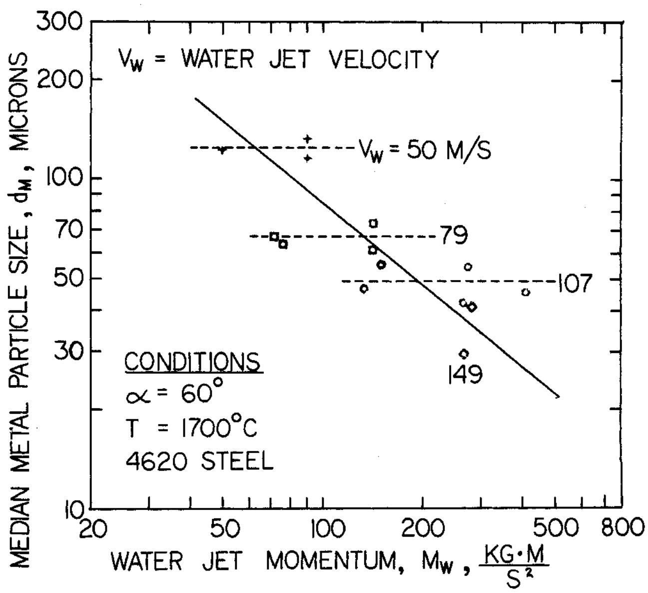

Fig. 8. Effect of water jet momentum on median metal size.

range of flow rate ratio studied. After this paper was presented (Grandzol and Tallmadge, 1972), the authors became aware of a study by Kishidaka (1972) in which a very small effect of mass flow rates was noted.

The authors have attempted to take some stop-action photographs of the breakup mechanism (Grandzol, 1973) but to date have succeeded only in observing the variations in the tundish stream before the apex. It is clear that high-speed photographs are important to clarifying the role of wave-ligaments and other possible mechanisms and in the development of improved models.

There are many other parameters which can profitably be studied for the water-metal system, most of which are reviewed in Rao et al. (1970, 1971) and Rao (1971). A few of these have been explored by the authors; some results are available in dissertation form (Grandzol, 1973).

Other metals have been atomized using the same equipment. A type 304 stainless steel produced a median size of 33μ (at V_w of 140 m/s), which agrees favorably with the data correlation. On the other hand, a cast iron run at V_w = 139 m/s produced a median size of 25μ, which is lower than the correlation. These results indicate the need for studying a wider range of metals, temperatures, and metal properties, and for testing the generality of the size equations.

There are also questions concerning other jet geometries. Although a choice of two jets was made here to simplify the modeling and photographing of the atomization process, more jets are often used in industry. It is therefore of interest to consider the influence of the effect of jet apex angle, the number of jets, the location of jets, and other geometric influences. Some data has been taken on angle and number of jets (Grandzol, 1973).

Atomization of liquid metals by impinging water jets is a major method for producing metal powders. However, there are several problems in scale-up from one process size to another. It is believed that development of models and correlations, such as those given herein, and determination of mechanisms will allow better design and economic utilization of two liquid atomization. One application is the use of metal powders to produce precision metal parts by powder metallurgy, which is becoming more important in the metal industries.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Defense under Themis Grant number DAAA-26-69-CO136.

NOTATION

A = metal parameter, Equation (1), mm²/s
B = water parameter, Equation (9), mm²/s
C = spray parameter, Equation (8)
C_v = coefficient of variation, Equation (3)
d^* = individual droplet diameter, microns (μ)
d_m = mass median metal particle diameter, microns (μ)
d_w = mass median water droplet diameter, microns (μ)
D = metal stream diameter, mm
M = momentum rate, kg-m/s²
P = manifold pressure, kN/m²
s = thickness of film, mm
T = tundish metal temperature, °C
V_m = metal particle velocity, m/s
V_w = water droplet velocity, m/s
W = mass flow rate of a fluid stream, kg/s

Greek Letters

γ = surface tension, N/mm
η = viscosity, N/m
ρ = density, g/cm³
σ = diameter ratio (or geometric standard deviation), Equation 2

Subscripts

m = metal
w = water

LITERATURE CITED

Anonymous, *Operating Characteristics of Descalejet Nozzles*, Spraying Systems Co., Bellwood, Ill. (1967).
Davies, J. T., *Turbulence Phenomena*, pp. 356-357, Academic Press, New York (1972).
Dombrowski, N., and P. C. Hooper, "The Effect of Ambient Density on Drop Formation in Sprays," *Chem. Eng. Sci.*, **17**, 291 (1962).
Eisenklam, P., "Atomisation of Liquid Fuel for Combustion," *J. Inst. Fuel*, **34**, 130 (1961).
Fraser, R. P., and P. Eisenklam, "Liquid Atomisation and the Drop Size of Sprays," *Trans. Inst. Chem. Engrs.*, **34**, 294 (1956).
———., and N. Dombrowski, "Atomisation in Chemical Engineering," *Brit. Chem. Eng.*, London, **2** (1957).
Grandzol, R. J., "Water Atomization of 4620 Steel and Other Metals," Ph.D. thesis, Drexel Univ., Philadelphia, Pa. (1973).
———., and J. A. Tallmadge, "Water Atomization of Molten Steel," paper presented in Symp. Transport Fund. Process Met, AIChE Annual Meeting, N. Y. (1972).
Gummeson, P. V., "Modern Atomizing Techniques," *Powder Met.*, **15**, 67 (1972).
Kishidaka, H., "Theory and Production of Atomized Iron Powder," *Proc. Multidisciplinary Mtg. Sintered Metals and Magnetic Materials*, Tokyo, Japan Soc. Powder Met., **19**, (1972).
Kruse, C. W., A. D. Hess, and G. F. Ludvik, "Performance of Liquid Spray Nozzles for Aircraft Insecticide Application," *J. Nat. Malaria Soc.*, **8**, 312 (1949).
Lapple, C. E., J. P. Henry, and D. E. Blake, "Atomization—A Survey and Critique of the Literature," Stanford Research Inst. Rept. #6, AD-831-314 (1967).
Merrington, A. C., and E. G. Richardson, "The Break-Up of Liquid Jets," *Proc. Phys. Soc.* (London), **59**, 1 (1947).
Perry, J. H., *Chemical Engineers' Handbook*, Chap. 23, pp. 31-51, 4th Edit., McGraw-Hill, N. Y. (1960).
Radcliffe, A., "The Performance of a Type of Swirl Atomizer," *Trans. Inst. Mech. Eng.*, **169**, 93 (1955).
Randolph, A. D., and M. A. Larson, *Theory of Particulate Processes*, pp. 32-33, Academic Press, New York (1971).
Rao, P., "Shape and Other Properties of Gas Atomized Metal Powders", Ph.D. Thesis, Chem. Engr. Dept., Drexel Univ. Phila., Pa. (1973).
———., "Quench Atomization of Liquid Metals," M.S. thesis, Drexel Univ., Philadelphia, Pa. (1971).
———., R. J. Grandzol, N. Schulz, and J. A. Tallmadge, "Quench Atomization of Iron-Base Alloys into Metal Powders," *J. Vacuum Sci. Tech.*, **7**, S132 (1970).
Rao, P., R. G. Bowrey, and J. A. Tallmadge, "Quench Atomisation-Optimisation Technology and Construction of a Research Unit," Proc. Chemeca 1970, Aust. Chem. Eng. Conf., Symp. on High Temp. Processes, 1-16, Butterworths, Sydney (1971).
Rao, P., and J. A. Tallmadge, "Change of Shape of Metal Droplets in Quench Atomization," 1971 Fall Powder Met. Conf. Proc., Metal Powder Industries Fed., New York (1972).
Small, S., and T. J. Bruce, "The Comparison of Characteristics of Water and Inert Gas Atomized Powders," *Intern. J. Powder Met.*, **4**, 7 (1968).
Smithells, C. J., *Metals Reference Book*, Vol III, pp. 668-669, 4th Edit., Plenum Press, New York (1967).
Straus, R., "The Mechanics of Formation of Liquid Droplets in Sprays," Ph.D. thesis, London University, England (1949).
Tanasawa, Y., and S. Toyoda, "On the Atomizing Characteristics of Injectors for Diesel Engines," *Technol. Rep. Tohoku Univ.*, **21**, 117 (1956).

Manuscript received December 21, 1972; revision received July 18 and accepted July 20, 1973.