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TERMINAL REPORT ON THE BOILING SLURRY
REACTOR EXPERIMENT (SLURREX)
(Mockup Hydraulic Experiments)

by

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PREFACE

A "Terminal Report on the Boiling Slurry Reactor Experiment (SLURREX)" was issued as ANL-6248.⁽¹⁾

At the termination of the SLURREX project, the half-scale mockup of the reactor system, which was to study the hydraulics of the reactor system, was in its final stage of construction. It was decided at that time that it would be desirable to complete the mockup hydraulic experiments and include the results as part of the documentation of the Reactor Engineering Division SLURREX effort.

This report contains the hydraulic analysis and the results of the mockup experiments.

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ABSTRACT

A half-scale mockup was built to study the hydraulics of the proposed SLURREX reactor system. Analysis of the pressure drop written as the summation of the frictional, acceleration, and hydrostatic head components around the closed flow loop yielded a hydraulic equation from which the circulation velocity can be computed:

$$307\alpha = 3.44 V_D^2 / 2g \quad .$$

Experimental results gave a velocity head coefficient of 3.20 as compared with the estimated value of 3.44. Static pressure taps were located at various points to check individual flow losses. The results indicated that most of the individual losses were overestimated, so that the higher velocity head coefficient was found.

I. INTRODUCTION

An analysis of the SLURREX natural-circulation system resulted in an hydraulic equation from which the circulation velocity can be calculated. However, this equation contains a degree of uncertainty since some of the hydraulic losses were guesses.

Generally, the performance of boiling reactors is dependent largely on the hydrodynamic characteristics of the reactor system. Therefore, an atmospheric pressure mockup of the reactor system was built to study the hydraulics and verify the derived hydraulic equation. Injected air was used to simulate steam voids.

II. MOCKUP FACILITY

A. Vessel

The proposed reactor system for the SLURREX experiment is shown as Figure 5 of ANL-6248.⁽¹⁾ The vessels and pipe sizes for the mockup were scaled down to half-diameter while maintaining the full riser

height. This reduced the fluid and air required to conduct an experimental program by a factor of four as compared with a full-scale test program. The system geometry was maintained in the mockup wherever practical so that similar hydraulic conditions would exist.

FIG. 1
HALF-SCALE MOCK-UP VESSEL

The mockup vessel is shown as Figure 1. The details of the mockup construction were given in Appendix A of ANL-6248.⁽¹⁾ In summary, the downcomers were 4-in. Schedule 40 piping and fittings, the re-entry section expanded from 4-in. to 5-in. to 12-in. piping, and the riser and steam separator were 12-in. Schedule 40 piping and fittings. The material of construction was carbon steel.

B. Air-injection System

The air entered the riser near the bottom through a hollow air-injection ring as shown in Figure 2. The ring contained thirty-six equally spaced, drilled holes of 0.64-cm diameter. A 2-in pipe connected the ring to the air

system. The air was supplied by a Roots-Connersville blower with a capacity of 11,300 ℓ (STP)/min, discharging at about 1.40 atm. Air flow was measured by orifice sections in parallel 1½-in. and 4-in. pipes.

C. Instrumentation

The downcomer velocities were determined using Fischer and Porter 10D1416A magnetic flowmeters. These were 10.2-cm ID, Teflon lined, with a velocity range of 0-350 cm/sec.

FIG. 2
RISER AIR INJECTION

The riser voids were determined by measuring the pressure difference between two diaphragm plates flush mounted 182 cm apart. The pressure signals were subtracted and transmitted by means of Taylor transaire differential transmitters Model No. 206TN195 to Taylor Model No. 63KF139 receiver gauges. The zero position for the D-P indicator had to be regularly reset. Every time the system was drained and refilled for an experimental change, the diaphragms returned to a slightly different position, so that the zero setting was altered.

The riser void fractions were also determined by the gamma-ray attenuation method as described in ANL-5766.⁽²⁾

The rate of air flow to the riser was measured with Foxboro type 22 flow indicators with ranges of 0-2270 $\ell(\text{STP})/\text{min}$ for the $1\frac{1}{2}$ -in. pipeline and 0-11,300 $\ell(\text{STP})/\text{min}$ for the 4-in. pipeline. The orifice diameters were 2.590 cm and 5.872 cm, respectively.

D. Separator

The separator was made of 12-in. Schedule 40 standard fittings arranged to obtain a continual slope to minimize slurry settling. A horizontal plate was placed above the riser to reduce liquid carryover.

Preliminary tests revealed that the separator design as shown in Figure 1 caused high downcomer void carryunder. The 12-in. pipe did not have sufficient distance between the fluid surface and the top of the separator to allow for the violent splashing caused by the bubbling air. Also, the rise in the splashing surface choked off the air exit. These conditions caused the high carryunder.

An open separator tank was designed and fabricated to eliminate the carryunder problem. The system with the new separator is shown in Figure 3. The open tank does not represent an answer to the SLURREX separator but only represents a simplification so that the hydraulic study could be completed.

FIG. 3
MODIFIED MOCK-UP VESSEL

Visual observation of the open separator tank showed that at riser voids of about 40%, splashing extended to between 60 to 100 cm above the fluid surface.

Problems arose because of rusting of the carbon steel system. The clear water quickly turned an orange color, and oxide powder was deposited on all the instrument probes and plastic viewing ports. The oxide deposit at one time shorted the magnetic flow meter electrodes. The oxide deposit on the D-P diaphragms changed slightly their flexing characteristics. During the interim period when the new separator tank was being fabricated, the entire inside surface of the mockup was painted. This eliminated the rusting problem, at least for the life of the experiment.

III. HYDRAULIC ANALYSIS

A. General

In a natural-circulation system the pressure drop around a closed loop is equal to zero. Therefore, the summation of the frictional, acceleration, and hydrostatic head components around the closed loop must be equal to zero.

$$\oint dP = 0 = \oint \rho dL + \oint \rho \frac{VdV}{g_c} + \oint \rho dH_f \quad (1)$$

where P is the pressure, ρ the density, V the velocity, H_f a head loss, L length, and g_c the gravity constant.

The flow geometry of the mockup can be visualized with the aid of Figure 3. The closed loop consists of the riser, separator tank, downcomer, and the 180-degree return Y fitting. Summation of the hydrostatic head components around the closed loop results in an expression which contains the density difference between the downcomer and the two-phase flow of the riser:

$$-\oint \rho dL = (\rho_D - \rho_R) L_R \quad , \quad (2)$$

where the subscripts D and R refer to the downcomer and riser, respectively, and L_R denotes the riser length. It is the density difference which is responsible for the driving force of the natural circulation. The acceleration and frictional components can be defined as the respective resistances which balance the driving force.

Hydraulic resistances or losses are generally defined as a multiplier (K) times the velocity head $V^2/2g_c$. The velocity term to be used in this expression will be V_D , the downcomer velocity. Summation of the frictional and acceleration components yields

$$\oint \rho \frac{VdV}{g_c} + \oint \rho dH_f = \rho(\Sigma K_C + \Sigma K_D) \frac{V_D^2}{2g_c} \quad , \quad (3)$$

where ΣK_C is the summation of the multipliers that are constant, functions of geometry only; and ΣK_D is the summation of the multipliers that vary with respect to α , the riser void fraction.

Combination of Equations (1), (2), and (3) results in the following equation:

$$(\rho_D - \rho_R) L_R = \rho(\Sigma K_C + \Sigma K_D)(V_D^2/2g_c) \quad . \quad (4)$$

The density of the riser is defined

$$\rho_R = \alpha \rho_a + (1 - \alpha) \rho_\ell \quad , \quad (5)$$

where subscripts a and ℓ refer to air and water, respectively.

The mockup water temperature was essentially constant. Also, the carryunder of air into the downcomers is assumed and later was verified to be negligible. Thus the downcomer fluid density, ρ_D , is equal to the water density, ρ_ℓ .

Combining Equations (4) and (5), and assuming the $\alpha \rho_g$ product to be negligible, there is obtained

$$\alpha L_R = (\Sigma K_C + \Sigma K_D)(V_D^2/2g_c) \quad . \quad (6)$$

Note that the density cancels out of the equation if the losses are based on the liquid density ρ_ℓ .

The effective hydraulic length L for the SLURREX reactor is made up of two parts, the riser and the core as shown in Equation (28) of ANL-6248.⁽¹⁾ However, for the mockup there is only the riser length L_R in the hydraulic equation since the air is injected only at one horizontal plane and not over the core vertical length as in the case of steam generation. The air-injection ring is located at a predetermined horizontal plane to simulate the riser and average core conditions of SLURREX. This plane, found to be about 8 in. below the core center, was determined by converting the core void fraction curve (see Figure 10, ANL-6248)⁽¹⁾ to a step function of one step. The mockup riser length, allowing for 30 cm of water depth in the separator tank, is 307 cm.

The frictional and accelerations losses will be determined by breaking down the mockup system into sections. The mockup geometry is: (1) the flow area of the core and riser is 722 cm² (12-in. Schedule 40 pipe); (2) the flow area of the downcomers is 164 cm² (two 4-in. Schedule 40 pipes); and (3) the flow area of the core entrance is 129 cm² (5-in. Schedule 40 pipe). The velocity relationships by mass balance are $V_D = 4.40 V_0$ and $V_{(5'')} = 1.27 V_D$, where V_0 is the water velocity in the riser based on a flow area of 722 cm² and $V_{(5'')}$ is the water velocity in the 5-in. Schedule 40 pipe.

B. The Downcomers

The hydraulic losses in the downcomers are due to the contraction and fluid acceleration caused by the area reduction from the separator tank into the downcomers, and the frictional loss for flow in the 4-in. downcomer. The contraction and acceleration loss, assuming the velocity head

in the separator tank to be negligible and a contraction coefficient of 0.5, is

$$\text{Loss} = \frac{V_D^2}{2g_c} + 0.5 \frac{V_D^2}{2g_c} = 1.5 \frac{V_D^2}{2g_c} \quad , \quad (7)$$

where

$$K_{C1} = 1.5 \quad .$$

An average Reynolds number for the downcomer flow was selected as 2.5×10^5 , as based on a minimum velocity of 90 cm/sec and a maximum velocity of 340 cm/sec at 21°C. The friction factor does vary with velocity and density, and therefore with Reynolds number. However, the range of conditions is in the relatively flat portion of the Reynolds pressure drop correlation; thus the friction factor tends to remain constant. The average friction factor f is 0.03. The frictional loss for 292 cm of 10.2-cm ID downcomer pipe is

$$\text{Loss} = \frac{fL_D}{D_D} \frac{V_D^2}{2g_c} = 0.86 \frac{V_D^2}{2g_c} \quad , \quad (8)$$

where

$$K_{C2} = 0.86 \quad .$$

C. 180-degree Return

The losses in the 180-degree return are due to the fittings which form the 180-degree return, flow friction, and the acceleration and contraction caused by the area reduction from the two downcomers to the 12.8-cm ID (5-in. Schedule 40) pipe.

The fittings loss coefficients⁽³⁾ are estimated as 0.2 for the 4-in. 90-degree, long radius elbow and 0.4 for the 4- to 5-in., 90-degree elbow. Thus, the 180-degree return fittings loss is

$$\text{Loss} = 0.6 \frac{V_D^2}{2g_c} \quad , \quad (9)$$

where

$$K_{C3} = 0.6 \quad .$$

The frictional loss for 76 cm of pipe bend is

$$\text{Loss} = 0.22 \frac{V_D^2}{2g_c} \quad , \quad (10)$$

where

$$K_{C4} = 0.22 \quad .$$

The acceleration and contraction loss, assuming that the contraction coefficient is negligible, is

$$\text{Loss} = \frac{V_5^2}{2g_c} - \frac{V_D^2}{2g_c} = 0.62 \frac{V_D^2}{2g_c} \quad , \quad (11)$$

where

$$K_{C5} = 0.62 \quad .$$

D. The Riser

The riser has the deceleration recovery and the losses due to void formation and two-phase frictional flow.

The deceleration recovery is caused by the flow expansion from the 12.8-cm ID (5-in. Schedule 40) pipe to the 30.3-cm ID (12-in. Schedule 40) pipe. The average expansion angle of 69 degrees gives a loss coefficient of 1.1 for gradual expansions.⁽⁴⁾ The gain for the expansion is

$$\text{Gain} = \frac{V_5^2}{2g_c} - \frac{V_0^2}{2g_c} = 1.1 \frac{(V_5 - V_0)^2}{2g_c} = 0.36 \frac{V_D^2}{2g_c} \quad , \quad (12)$$

where

$$K_{C6} = -0.36 \quad .$$

The acceleration loss due to void formation caused by air injection, based on a momentum balance, is

$$\text{Loss} = \frac{V_0}{g_c} \left(\frac{V_0}{1 - \alpha} - V_0 \right) = \frac{0.10\alpha}{1 - \alpha} \frac{V_D^2}{2g_c} \quad , \quad (13)$$

where

$$K_{D1} = \frac{0.10\alpha}{1 - \alpha} \quad .$$

The calculation of the two-phase frictional loss in the riser is slightly complicated by the existence of four fixed, simulated neutron poison vanes. The average Reynolds number for the two-phase flow is about 80,000, based on an equivalent diameter (D_{eq}) of 13.7 cm.

The average friction factor f is 0.028, and the riser length is 276 cm. The loss for the two-phase flow friction is

$$Loss = \frac{fL_R}{D_{EQ}} \frac{1}{(1-\alpha)^2} \frac{V_0^2}{2g_c} = \frac{0.029}{(1-\alpha)^2} \frac{V_D^2}{2g_c} \quad , \quad (14)$$

where

$$K_{D2} = \frac{0.029}{(1-\alpha)^2} \quad .$$

E. The Separator Tank

The flow loss in the separator tank between the riser and the downcomers is negligible.

The summation of the K_C coefficients is 3.44, and the summation of the K_D coefficients is

$$\Sigma K_D = \frac{0.10\alpha}{1-\alpha} + \frac{0.029}{(1-\alpha)^2} \quad . \quad (15)$$

Once the system geometry is selected, as it has been in Figure 3, the K_C 's are constant and the K_D 's are a function only of void fraction.

Substitution of ΣK_C and the ΣK_D into Equation (6) yields the hydraulic equation of the SLURREX mockup, from which the circulation velocity can be computed:

$$307\alpha = \left[3.44 + \frac{0.10\alpha}{(1-\alpha)} + \frac{0.029}{(1-\alpha)^2} \right] \frac{V_D^2}{2g_c} \quad . \quad (16)$$

The experimental values of α varied from 0.10 to 0.50. Thus, the value of ΣK_C varied from 0.05 to 0.22, respectively. The values of ΣK_D are considered negligible as compared with the value of ΣK_C over the void fraction (α) range investigated. This simplifies Equation (16) to

$$307\alpha = 3.44 \frac{V_D^2}{2g_c} \quad . \quad (17)$$

It should be noted that the controlling hydraulic resistances are the external resistances because the boiling slurry reactor core (internal resistance) is essentially hydraulically clean. With a fixed core, like the EBWR, the controlling resistance is the reactor core with its small flow channels.

F. One-downcomer System

Hydraulic analysis for flow through only one downcomer, the second downcomer being blocked, is presented. The new velocity relationships by

mass balance are $V_D = 8.79 V_0$ and $V_{(5'')} = 0.636 V_D$. The mockup will be divided up into the same sections as before for analysis.

The losses for the downcomer section will be identical with the ones previously determined as Equations (7) and (8); thus,

$$K_{C1} = 1.5 \text{ and } K_{C2} = 0.86 \quad .$$

The fitting and frictional losses for the 180-degree return will be the same. Thus,

$$K_{C3} = 0.6 \text{ and } K_{C4} = 0.22 \quad .$$

However, since there is only one downcomer, the flow from the downcomer into the 5-in. pipe will undergo an expansion rather than a contraction. The 7-degree expansion angle for the 90-degree expanding elbow gives a loss coefficient of 0.2 for gradual increases.⁽³⁾ The gain for expansion is

$$\text{Gain} = \frac{V_D^2}{2g_c} - \frac{V_{5''}^2}{2g_c} - 0.2 \frac{(V_D - V_{5''})^2}{2g_c} = 0.57 \frac{V_D^2}{2g_c} \quad , \quad (18)$$

where

$$K_{C5} = -0.57 \quad .$$

The riser deceleration recovery for the flow expansion from the 5-in. to the 12-in. pipe, similar to Equation (12), is

$$\text{Gain} = \frac{V_{5''}^2}{2g_c} - \frac{V_0^2}{2g_c} - 1.1 \frac{(V_{5''} - V_0)^2}{2g_c} = 0.09 \frac{V_D^2}{2g_c} \quad , \quad (19)$$

where

$$K_{C6} = -0.09 \quad .$$

The acceleration loss due to void formation and the two-phase frictional loss are negligible over the void fraction range investigated as before.

The flow loss in the separator tank is negligible.

The summation of the K_C coefficients substituted into the general hydraulic equation, Equation (6), yields

$$307\alpha = 2.52 V_D^2 / 2g_c \quad . \quad (20)$$

IV. EXPERIMENTAL RESULTS

A. Two-downcomer System

The experimental results are shown in Figures 4 and 5. The experimental correlation yields an hydraulic equation of

$$307\alpha = 3.20 V_D^2/2g_c \quad , \quad (21)$$

where ΣK_C is the slope of the correlation line. The summation of K_C is, experimentally, 3.20 as compared with 3.44 in Equation (17).

FIG. 4
EXPERIMENTAL RESULTS
DOWNCOMER VELOCITY VS VOID FRACTION

FIG. 5
EXPERIMENTAL RESULTS
DOWNCOMER VELOCITY HEAD VS VOID FRACTION

Orifice plates to serve as additional external hydraulic resistances were added in the downcomers. The results are plotted in Figure 6. The experimental correlations for the 8.57-cm diameter plate (line B), the 7.62-cm diameter plate (line C), and the 6.35-cm diameter plate (line D) results in resistance summations ΣK_C of 4.34, 6.66, and 15.40 downcomer velocity heads, respectively. Thus the hydraulic resistance coefficient for the 8.57-cm diameter plate is 1.10 downcomer velocity heads, for the 7.62-cm diameter plate is 3.46, and for the 6.35 cm diameter plate is 12.2.

Fig. 6

Experimental Results, Downcomer Velocity Head vs Void Fraction for Various Downcomer Resistances

B. One-downcomer System

The experimental results for one downcomer shown in Figure 7 yield an hydraulic correlation of

$$307\alpha = 2.48 V_D^2/2g_c \quad (22)$$

Fig. 7

Experimental Results, Downcomer Velocity Head vs Void Fraction for Various Downcomer Resistances Using One Downcomer Only

The experimental summation of K_C is 2.48 as compared with 2.52 of Equation (20). The same orifice plates as previously used had resistance summations ΣK_C for the one downcomer system of 3.66, 6.16, and 15.38 downcomer velocity heads, respectively. Thus, the resistance plate coefficients were 1.18, 3.68, and 12.9 downcomer velocity heads, respectively. This compares favorably with the resistance plate coefficients previously determined for two-downcomer flows.

In both cases, the hydraulic coefficients were overestimated. This is due mainly to the overestimation of the 180-degree return resistance, which will be shown later.

The circulation data used in plotting the curves are given in Appendix A.

C. Individual Flow Losses

Static pressure taps were used at various points on the mockup to check the flow losses of the downcomer and the 180-degree return sections. The taps were located as shown in Figure 8, with the ends of the tubes being open to the atmosphere above the separator liquid level. The difference in the liquid level of the taps represented the static pressure drop between the points of interest.

Fig. 8
Static Pressure Tap Locations
on the Mockup

Figure 9 shows the tap pressure difference with respect to downcomer velocity head for section 1 to 2 and 2 to 3 of Figure 8. A Bernoulli's equation balance between 1 and 2 yields

$$\frac{\Delta P}{\rho} = (k_c + 1) \frac{V_D^2}{2g_c} \quad , \quad (23)$$

where $\Delta P/\rho$ is the pressure difference expressed in cm of water and k_c is the contraction coefficient from the separator tank into the downcomer. The slope of the point 1 to 2 line is 1.45, giving k_c a value of 0.45. The estimated k_c value was 0.50 for a sharpened edge entrance. The lower contraction coefficient is believed to be caused by the very slight rounding of the entrance edge.

FIG. 9
DOWNCOMER VELOCITY HEAD VS STATIC
PRESSURE DIFFERENCE FOR SECTIONS 1 - 2 AND 2 - 3

The Bernoulli equation balance between 2 and 3 gives

$$\frac{\Delta P}{\rho} = K_{C2} \frac{V_D^2}{2g_c} \quad , \quad (24)$$

where K_{C2} is the downcomer frictional loss. The value of K_{C2} determined from the point 2 to 3 experimental line of Figure 9 is 1.1 as compared with an estimated value of 0.86. Apparently not enough consideration was given to the surface roughness; thus the estimated value was low. The rusting carbon steel resulted in a surface rougher than normal.

Figure 10 covers the pressure tap difference for sections 3 to 4 and 4 and 5. Note that different results were obtained depending on whether one or two downcomers were used.

FIG. 10
DOWNCOMER VELOCITY HEAD VS STATIC PRESSURE
DIFFERENCE FOR SECTIONS 3 - 4 AND 4 - 5

For section 3 to 4, two-downcomer flow resulted in a contraction, whereas one-downcomer flow resulted in a flow expansion. Bernoulli's equation balance between 3 and 4 for two downcomers gives

$$\frac{\Delta P}{\rho} = (k_a + 0.62) \frac{V_D^2}{2g_C} \quad , \quad (25)$$

and for one downcomer gives

$$\frac{\Delta P}{\rho} = (k_e - 0.60) \frac{V_D^2}{2g_c} \quad , \quad (26)$$

where k_a is the sum of the friction, fitting, and acceleration coefficients; and k_e is the sum of the friction, fitting, and expansion coefficients. Figure 10 gives experimental values of $k_a = 0.42$ and $k_e = 0.75$, whereas the estimated values are 0.82 and 0.85, respectively. The difference in values is due to overestimation of the fitting loss coefficients and the expansion or contraction coefficient.

For section 4 to 5, translation from V_0 to V_D effects the loss coefficient, since the velocity relationship is different for the one- or two-downcomer case. Bernoulli's equation balance between points 4 and 5 across the 5-in. to 12-in. expansion for two downcomers yields

$$\frac{\Delta P}{\rho} = (k_{e2} - 1.57) \frac{V_D^2}{2g_c} \quad , \quad (27)$$

and for one downcomer yields

$$\frac{\Delta P}{\rho} = (k_{e1} - 0.39) \frac{V_D^2}{2g_c} \quad , \quad (28)$$

where the k_e 's are the expansion loss coefficients. Figure 10 gives experimental values for k_{e2} of 1.29 and for k_{e1} of 0.27, whereas the estimated values were 1.21 and 0.30, respectively.

Thus, the experimental determination of the various section loss coefficients verified the coefficient estimates made were reasonable.

The experimental data are given in Appendix B.

D. Noncirculating Tests

A series of runs (see Appendix C) were conducted with both downcomers blocked. This can be described as the case of infinite flow resistance, since there is no fluid recirculation through the downcomers. A curve giving the variance of the riser void fraction α with respect to the summation of the flow resistance coefficients for a constant volumetric riser air flow rate is shown in Figure 11. The flow resistance coefficients are based on the $V_0^2/2g_c$ velocity head term for compatibility. The reciprocals of the resistance coefficients (Appendix D) are used so that the riser void fraction for the infinite resistance case can be plotted at zero.

FIG. 11
VOID FRACTION VS LOSS COEFFICIENT RECIPROCAL

APPENDIX A

Table I

CIRCULATION DATA, TWO DOWNCOMERS

Air Injection Rate, ℓ (STP)/min	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α	Air Injection Rate, ℓ (STP)/min	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α
42	133	0.09	48	153	0.13
57	166	0.14	57	160	0.14
71	176	0.16	71	176	0.16
85	188	0.18	85	194	0.20
105	198	0.21	105	201	0.21
125	207	0.23	125	211	0.23
142	213	0.24	144	218	0.25
170	222	0.26	170	223	0.27
241	240	0.31	241	240	0.31
340	262	0.37	340	261	0.37
425	274	0.41	425	277	0.41
566	296	0.47	510	289	0.45

Table II

CIRCULATION DATA, TWO DOWNCOMERS AND
THE 8.57-cm DIA. RESISTANCE PLATES

Air Injection Rate, ℓ (STP)/min	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α	Air Injection Rate, ℓ (STP)/min	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α
42	122	0.11	425	233	0.39
57	138	0.14	566	252	0.46
71	151	0.17			
85	161	0.19	57	143	0.15
105	169	0.21	85	162	0.19
125	178	0.23	125	179	0.23
144	185	0.25	170	192	0.25
170	190	0.26	241	210	0.31
241	204	0.29	425	239	0.40
340	220	0.35	566	254	0.46

Table III

CIRCULATION DATA, TWO DOWNCOMERS AND
THE 7.62-cm DIA. RESISTANCE PLATES

Air Injection Rate, ℓ (STP)/min	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α	Air Injection Rate, ℓ (STP)/min	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α
42	99	0.11	425	193	0.42
57	112	0.14	566	208	0.48
71	122	0.17			
85	131	0.19	57	113	0.14
105	137	0.21	85	131	0.19
125	144	0.23	125	143	0.23
144	150	0.25	170	153	0.26
170	154	0.26	241	169	0.32
241	167	0.31	425	193	0.42
340	180	0.36	538	205	0.46

Table IV

CIRCULATION DATA, TWO DOWNCOMERS AND
THE 6.35-cm DIA. RESISTANCE PLATES

Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α	Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α
42	71	0.13	510	137	0.48
57	80	0.16	566	141	0.51
71	86	0.19			
85	91	0.21	57	76	0.15
105	95	0.23	85	90	0.21
125	99	0.25	125	99	0.25
144	102	0.27	170	105	0.28
170	105	0.28	241	114	0.33
241	109	0.31	425	130	0.43
340	123	0.39	538	139	0.49
425	131	0.44			

Table V

CIRCULATION DATA, ONE DOWNCOMER

Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α	Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α
42	149	0.10	93	225	0.21
57	183	0.14	113	231	0.22
71	199	0.17	133	241	0.24
85	212	0.19	156	254	0.27
105	230	0.22	190	267	0.30
125	237	0.23	289	289	0.36
144	248	0.25	382	308	0.41
170	257	0.28	467	324	0.44
241	278	0.33	566	335	0.47
312	296	0.37			
425	314	0.42	57	193	0.15
510	330	0.46	85	226	0.21
			125	245	0.25
42	164	0.11	170	258	0.27
48	178	0.13	241	285	0.34
62	195	0.16	425	319	0.43
76	208	0.18	538	341	0.48

Table VI

CIRCULATION DATA, ONE DOWNCOMER AND
A 8.57-cm DIA. RESISTANCE PLATE

Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α	Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity V_D , cm/sec	Riser Void Fraction α
42	134	0.11	170	217	0.29
57	157	0.15	241	230	0.32
71	172	0.18	340	251	0.39
85	185	0.21	425	266	0.43
105	193	0.23	510	280	0.47
125	203	0.25	566	287	0.50
144	209	0.26			

Table VII

CIRCULATION DATA, ONE DOWNCOMER AND
A 7.62-cm DIA. RESISTANCE PLATE

Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity $V_D, \text{cm/sec}$	Riser Void Fraction α	Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity $V_D, \text{cm/sec}$	Riser Void Fraction α
42	110	0.13	510	216	0.48
57	125	0.17	566	224	0.51
71	135	0.20			
85	143	0.22	57	130	0.18
105	149	0.24	85	152	0.23
125	156	0.26	125	166	0.28
144	162	0.28	170	175	0.31
170	171	0.30	241	190	0.35
241	179	0.34	425	216	0.45
340	197	0.40	566	229	0.52
425	209	0.45			

Table VIII

CIRCULATION DATA, ONE DOWNCOMER AND
A 6.35-cm DIA. RESISTANCE PLATE

Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity $V_D, \text{cm/sec}$	Riser Void Fraction α	Air Injection Rate, $\ell(\text{STP})/\text{min}$	Downcomer Velocity $V_D, \text{cm/sec}$	Riser Void Fraction α
42	73	0.14	170	110	0.31
57	81	0.18	241	116	0.36
71	86	0.21	340	127	0.41
85	94	0.24	425	134	0.47
105	99	0.26	510	140	0.50
125	103	0.28	566	142	0.53
144	106	0.30			

APPENDIX B

Table IX

STATIC PRESSURE DIFFERENCE,
SECTION 1-2 OF FIGURE 8

Downcomer Velocity V_D , cm/sec	D-P, cm water	Downcomer Velocity V_D , cm/sec	D-P, cm water
164	20-1/2	113	11-1/2
178	24	131	14
195	27-1/2	143	16
208	33	153	19
225	37-1/2	169	22
231	40-1/2	193	29
241	44-1/2	205	31-1/2
254	47-1/2		
267	52-1/2	143	15
289	60-1/2	162	20
308	67	179	24
324	76	192	27
335	80	210	32
		239	42
153	17	254	47
160	19		
176	23	76	4-1/2
194	27	90	6
201	30-1/2	99	7-1/2
211	32-1/2	105	8-1/2
218	34	114	10
223	36	130	13
240	42	139	14-1/2
261	48-1/2		
277	54-1/2		
289	59		

Table X

STATIC PRESSURE DIFFERENCE,
SECTION 2-3 OF FIGURE 8

Downcomer Velocity V_D , cm/sec	D-P, cm water	Downcomer Velocity V_D , cm/sec	D-P, cm water
164	16	153	12-1/2
178	18	160	14
195	21	176	17-1/2
208	25-1/2	194	20
225	31	201	22
231	32	211	25
241	34-1/2	218	26-1/2
254	37	223	27
267	40	240	30
289	48	261	38
308	52	277	40
324	57	289	47
335	62		

Table XI

STATIC PRESSURE DIFFERENCE, SECTION 3-4
OF FIGURE 8 USING TWO DOWNCOMERS

Downcomer Velocity V_D , cm/sec	D-P, cm water	Downcomer Velocity V_D , cm/sec	D-P, cm water
153	13	218	27-1/2
160	15	223	29
176	18	240	33
194	21-1/2	261	40
201	23-1/2	277	44-1/2
211	25-1/2	289	47-1/2

Table XII

STATIC PRESSURE DIFFERENCE, SECTION 4-5
OF FIGURE 8 USING TWO DOWNCOMERS

Downcomer Velocity V_D , cm/sec	D-P, cm water	Downcomer Velocity V_D , cm/sec	D-P, cm water
153	- 2-1/2	218	- 7-1/2
160	- 3	223	- 7-1/2
176	- 3-1/2	240	- 8-1/2
194	- 5	261	-10
201	- 6	277	-13
211	- 7		

Table XIII

STATIC PRESSURE DIFFERENCE, SECTION 3-4
OF FIGURE 8 USING ONLY ONE DOWNCOMER

Downcomer Velocity V_D , cm/sec	D-P, cm water	Downcomer Velocity V_D , cm/sec	D-P, cm water
164	2	254	5
178	3	267	5-1/2
195	3	289	6-1/2
208	3-1/2	308	7-1/2
225	4	324	8-1/2
231	4	335	9
241	4-1/2		

Table XIV

STATIC PRESSURE DIFFERENCE, SECTION 4-5
OF FIGURE 8 USING ONLY ONE DOWNCOMER

Downcomer Velocity V_D , cm/sec	D-P, cm water	Downcomer Velocity V_D , cm/sec	D-P, cm water
164	-2	241	-4
178	-2	254	-4-1/2
195	-2-1/2	267	-4-1/2
208	-3	289	-5-1/2
225	-3-1/2	308	-6
231	-4	324	-6-1/2

APPENDIX C

Table XV

NONCIRCULATING DATA
(Both Downcomers Blocked)

Air Injection Rate, $\ell(\text{STP})/\text{min}$	Riser Void Fraction α
42	0.17
57	0.19
71	0.23
85	0.26
105	0.29
125	0.32
144	0.34
170	0.36
241	0.41
340	0.48
425	0.54
510	0.57
566	0.59

APPENDIX D

Table XVI

TOTAL FLOW RESISTANCES
AND THEIR RECIPROCAL

Number of Downcomers Used	Orifice Plate Dia., cm	$\sum K_c$ Velocity Head Basis $V_D^2/2g_c$	$\sum K_{cv_0}$ Velocity Head Basis $V_0^2/2g_c$	Reciprocal, $\frac{1}{\sum K_{cv_0}}$
2	NONE	3.20	61.8	0.0162
2	8.57	4.34	83.8	0.0119
2	7.62	6.66	129	0.00775
2	6.35	15.40	298	0.00336
1	NONE	2.48	192	0.00521
1	8.57	3.66	283	0.00353
1	7.62	6.16	476	0.00210
1	6.35	15.38	1190	0.00084

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