AN EXPERIMENTAL STUDY OF THE HYDRODYNAMIC TRANSPORT OF SPHERICAL AND CYLINDRICAL CAPSULES IN A VERTICAL PIPELINE

By

© KIN-WAI CHOW, B.A.Sc. (Ottawa)

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AUTHOR: Ken K. W. Chow, B.A.Sc. (University of Ottawa)

SUPERVISOR: Dr. B. Latto

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ABSTRACT

This thesis is concerned with the flow phenomena associated with the hydraulic transport of spherical and cylindrical capsules in a 7.6 cm-diameter vertical pipeline.

In the experiments, spherical capsules of steel, aluminum and nylon of capsule/pipe diameter ratio $d/D = 0.57$, 0.65 and 0.82 were investigated. Also, right circular cylinders of aluminum and nylon of $d/D = 0.49$, 0.65, 0.82, and capsule length/diameter ratio $L/d = 4$, 7, 10, 14 were investigated. The steady-state capsule velocity V_c and the pressure gradient associated with the capsules were measured. Based on the measured results the velocity ratio R_v, the pressure gradient R_p and the unit energy requirements $\underline{P}$ for the capsules were calculated. The effects of the individual pertinent variables which affect R_v, R_p and $\underline{P}$ as indicated by the experiments were discussed.

Furthermore, theoretical and semi-empirical correlations between V_c, $(\Delta P/L)_c$ and the pertinent variables of the systems were derived.

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NOMENCLATURE

A	Area
a	Empirical constant
b	Empirical constant
c	Empirical constant
C_d^*	Drag coefficient defined by Equation (3.7) to (3.10)
C_{d_1}	Drag coefficient defined by Equations (3.15)
C_{d_2}	Drag coefficient defined by Equations (3.15)
C_{d_3}	Drag coefficient defined by Equations (3.16)
D	Pipe diameter
d	Capsule diameter
e_c	Capsule surface roughness
e_p	Pipe surface roughness
E	Energy consumption for capsules
f	Friction factor
g	Local acceleration due to gravity 9.806 m/s^2
K	Capsule to pipe diameter ratio, d/D
L	Capsule length (or L_c)
L_p	Length of test section of pipeline
L/d	Capsule length to diameter ratio
$\dot{m}$	Capsule mass flowrate
$(\Delta P/L)_c$	Total pressure gradient across capsule
$(\Delta P_o/L)$	Pressure gradient due to the presence of the capsule
$(\Delta P/L)_L$	Pressure gradient in the free pipe due to the fluid alone

$\underline{P}$ Unit energy requirements for the capsule

q Empirical constant in Equation (3.22)

R_v Velocity ratio = $\frac{V_c}{V_{av}}$

R_p Pressure gradient ratio = $(\Delta P/L)_c/(\Delta P/L)_L$

Re_D Reynold's number based on D and V_{av}

Re_N Reynold's number based on (D-d) and V_N

S_c Capsule specific gravity

t Time

T Temperature

$\dot{V}$ Capsule volumetric flowrate

V_{av} Average water velocity in the test section

V_c Capsule velocity

V_N Water velocity in the annulus space between pipe and capsule

W_B Buoyed weight of the capsule

ρ Water density

σ Capsule density

τ_c Shear stress on the capsule wall

τ_p Shear stress on the pipe wall

μ Dynamic viscosity of water

Subscripts

av Average value

c Capsule

L Liquid

N Annular

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Over the past two decades there has been an increasing interest in efficient transport of material in pipelines as an alterative to more conventional methods. The transport of capsules has some attractive features in that a specific material can be separated from the transporting fluid.

In the mid 1960's the majority of research on capsule pipelining was being primarly done at the Research Council of Alberta (ARC). In the late 1960's and 1970's considerable exploratory studies have been underway at McMaster University.

The work done at the Research Council of Alberta were mainly concerned with horizontal pipeline while that carried out at McMaster was concerned with stationary capsules either rigidly mounted or freely suspended in vertical pipelines using water or aqueous polymer solution as the working fluid.

No research, however, had been performed on the dynamic aspects of moving capsules in a vertical pipeline until the present study, in spite of the fact that capsule flow in vertical pipeline could form a major part of capsule and/or regular body pipelining.

Capsule flow in a vertical pipeline could have a wide range of applications in areas such as deep sea or underground mining and chemical processes in general. It is expected that capsule flow in a vertical pipeline behaves considerably differently from that in horizontal pipeline. Therefore, in order to supplement the existing knowledge of capsule pipelining and provide necessary information for the design of future capsule pipeline systems, extensive research on vertical pipeline capsule flow is needed. This is the purpose of the study reported in this thesis.

In the present study, the hydrodynamic effects of some specific variables such as fluid velocity, capsule diameter, length and density on the capsule velocity and pressure gradient across the capsule were studied. Attempts were also made to correlate the afromentioned variables to capsule velocity and pressure gradient for both cylindrical and spherical capsules.

The present investigation was carried out in a 11-meter vertical length of 7.6 cm diameter 40-schedule steel pipe using water as the carrier fluid. Spherical capsules of steel, aluminum and nylon of capsule/pipe diameter ratio of 0.57, 0.65 and 0.82 were investigated. Also right circular cylindrical capsules of aluminum and nylon of 0.49, 0.65 and 0.82 diameter ratio and 4, 7, 10, 14 of length/diameter ratio were investigated. The fluid velocity covered the range from 0.3 to 5.5 m/s.

CHAPTER 2

LITERATURE SURVEY

The idea of transport of material in pipeline in the form of capsules was reinitiated in a paper by Hodgson and Charles (3).

The idea was developed from the observation of the flow pattern of equal-density oil-water flow in a horizontal pipe. They noted that the oil bodies occupied the region of the pipe where the linear velocity in both laminar and turbulent flow was significantly greater than the average velocity for the pipe flow as a whole. Secondly, they observed that the pressure gradient in turbulent flow was somewhat less than that with the carrier liquid flowing alone. Therefore, a favourable velocity and pressure gradient might be anticipated if the oil slugs were substituted by solid bodies which were subsquently called capsules.

These findings led to the proposal of practical capsule pipelining which resulted in extensive theoretical and experimental studies over a fifteen year period at the Research Council of Alberta (ARC). A series of papers concerning these researches was published (3-13, 26, 28, 30-32, 35-37) during the period from 1963 to 1975.

In the second part of the series of articles, Charles (4) presented a theoretical analysis of the concentric flow of long cylindrical capsule carried in equidensity liquid in both laminar and turbulent motion. The following analytical solutions for the capsule velocity and pressure gradient across the capsule were obtained:

$$V_c = \frac{2}{1+K^2} V_{av} \qquad \text{(Laminar)} \tag{2.1}$$

$$V_c = \frac{V_{av}}{[4/7K(1-K)+49/60(1-K)^2+K^2]} \qquad \text{(Turbulent)} \tag{2.2}$$

$$\left(\frac{\Delta P}{L}\right)_{c-\ell} = \left(\frac{1}{1-k^4}\right)\left(\frac{\Delta P}{L}\right)_{f-\ell} \tag{2.3}$$

(For laminar flow in both annulus and free-stream)

$$\left(\frac{\Delta P}{L}\right)_{c-t} = \left[\frac{.82}{(1-K)^{1/7}(T/4K(1-K)+49/60(1-K)^2+K^2)}\right]^{1.75}\left(\frac{\Delta P}{L}\right)_{f-t} \tag{2.4}$$

(For turbulent flow in both annulus and free-stream)

$$\left(\frac{\Delta P}{L}\right)_{c-\ell,t} = \frac{202}{(1-K)^4(Re_D)^{3/4}}\left(\frac{\Delta P}{L}\right)_{f-t} \tag{2.5}$$

(For laminar in annulus and turbulent in free-stream)

(For $Re_D = \frac{\rho V_{AV} D}{\mu} > 2000$)

where $(\frac{\Delta P}{L})$ = pressure gradient with subscripts, c stands for capsule, f for fluid, ℓ for laminar and t for turbulent respectively.

Equations (2.1) and (2.2) show that V_c is always greater than V_{av} for equidensity capsule flow. Equation (2.3) and (2.4) show that $(\frac{\Delta P}{L})_c$ is always greater than $(\frac{\Delta P}{L})_f$ while for the case of laminar flow in an annulus with a turbulent free-stream, i.e. Equation (2.5), indicates that $(\frac{\Delta P}{L})_c$ does not necessarily exceed $(\frac{\Delta P}{L})_{f-t}$ and therefore that the presence of a capsule in an equidensity fluid does not necessarily increase the pressure gradient.

Experiments were then carried out in the ARC to verify the viability of the models set out by this analysis. Since the flow considered in the analysis represents the most idealized case experimental values were expected to be somewhat less than the prediction. However, comparison of the experimental results (5,6,7) showed the reverse. This was particularly evident for some cases when there was turbulent annular and core flow. Attempts by the researchers to explain this discrepancy were unsatisfactory until Kennedy (14) introduced another set of equations.

Kennedy in the analysis of plug flow found that Charles' analysis did not account for the slip which Kennedy termed as slip velocity in the viscous sublayer next to the capsule boundary. Kennedy's argument was that since the capsule boundary is impermable, force transfer by the interchange of fluid momentum is blocked. A viscous sublayer, within which the intensity of viscous shear is sufficiently high to accomplish the transfer, must exit. This led to the following equations developed by Kennedy for the turbulent-turbulent case:

$$V_c = \frac{V_{av}+V_L[7/4K(1-K)+49/60(1-K)^2]}{[7/4K(1-K)+49/60(1-K)^2+K^2]} \tag{2.6}$$

where

$$V_L = \frac{B\sqrt{\frac{r_c}{2\rho}\left|\frac{\Delta P}{L}\right|_f}}{1.22(1-K)^{1/7}[\frac{7}{4}K(1-K)+\frac{49}{60}(1-K)^2+K^2]+\frac{BK^2}{V_{AV}}\sqrt{\frac{r_c}{2\rho}(\frac{\Delta P}{L})_f}} \tag{2.7}$$

and B is a constant with value between 11-13.

$$(\frac{\Delta P}{L})_c = [\frac{0.82(1-K^2)\frac{V_L}{V_{av}}}{[\frac{7}{4}K(1-K)+\frac{49}{60}(1-K)^2+K^2](1-K^{1/7})}]^{1.75}(\frac{\Delta P}{L})_{f-t} \tag{2.8}$$

Comparison of Equation (2.6) with (2.2) shows that the value of V_c is higher from the former than the latter, and Equation (2.8) predicts a decrease of $(\frac{\Delta P}{L})_c$ with an increase in K, the reverse of the original prediction by Charles neglecting V_L. Comparison of (2.6) to Ellis' experimental result and (2.8) to the observation made in plug flow supported Kennedy's contention.

Nevertheless Charles' analysis, for the other flow regions of concentric equal-density long cylindrical capsule flow, is still useful and in fact formed a basis of comparison for the subsquent experiments.

The main object of the series of research (4-12) was to study the hydrodynamics of capsule flow and to investigate the effects of all the parameters which might affect the capsule velocity and the change of pressure gradient.

The parameters used, in dimensionless form, were namely: Re, $\frac{\sigma-\rho}{\rho}$, d/D, L/d, end shapes, ℓ_c/d, and $\ell p/D$ (see Nomenclature).

Some understandings of the effect of each of the above parameters on the velocity ratio (V_c/V_{av}) and the capsule pressure gradient were obtained from the ARC research and the results may be classified as follows:

1) The Reynolds number: Several different forms of Reynolds number including the pipe Reynolds number were used in the experimental results. The form of the Re based on the annulus space and velocity i.e. $Re_{ann} = \frac{\rho V_{ann}(D-d)}{\mu}$ was employed in a correlation with the friction factor, which in effect determines the shear force exerted by the fluid on the side of the capsule. Satisfactory results were obtained by using Re_{ann} in the correlation of

$$(fRe^m)_{ann} = C \text{ to predict } f_{ann} \quad (12, 31)$$

For practical convenience the Reynolds number is usually based on the conditions in the pipe upstream of the capsule and was consequently used for correlation involving V_c/V_{av} and $(\Delta P/L)_c$.

The general trend was that the velocity ratio V_c/V_{av} increased with an increase of Re_D. However the pressure gradient, $(\Delta P/L)_c$ might decrease or increase with increase of Re_D depending on the flow in the annulus around the capsule.

2) <u>The apparent density ratio</u> - $(\frac{\sigma-\rho}{\rho})$ or (S_c-1)

Solid and hollow capsules of different specific gravity ranging from 1 to 8 were used in the investigations.

It was found that V_c/V_{av} decreased with increase of density ratio but the effect was not so marked for spheres as for cylinders and $(\Delta P/L)_c$ increased with increase of $(\frac{\sigma-\rho}{\rho})$.

3) <u>The capsule to pipe diameter ratio (d/D)</u>:

Apparently V_c/V_{av} increased with increase of d/D for both spherical and cylindrical capsules of density greater than the carrier fluid. But the opposite was the case for equidensity capsules (5, 9). The reason was that in the case where capsule was denser than the fluid, the capsule was sliding along the bottom of the pipe, hence a larger diameter capsule was situated in a higher fluid velocity region. On the other hand, an equidensity capsule was floating and travelling in concentric position, hence a smaller capsule would occupy a higher fluid velocity region.

4) <u>The capsule length/diameter ratio (L/d)</u>:

It was also observed that V_c/V_{av} increased with a decrease of L/d when $V_c/V_{av} < 1$, but the reverse when $V_c/V_{av} > 1$ (5, 6, 9, 10).

5) <u>The end shape</u>

An ellipsoidal nose was found to increase velocity ratio and to decrease pressure gradient for capsules of small diameter ratio. There was little effect for $d/D > .8$ (5, 6, 10).

6) <u>Surface roughness of capsule and pipe</u>

It was also found that usually an increase of roughness for either the pipe or capsule surface or both resulted in reduction of velocity ratio and increased the pressure gradient at low velocity but the effects disappeared at high velocities (6, 10, 30, 31).

In conjunction with the parameters mentioned above several other parameters were introduced into the initial analysis. These parameters were mainly discussed in two theoretical investigations made on eccentric capsule flow the conditions for which most of the experiments were frequently encountered.

In part 6 of the ARC series Newton et al (8) presented results of a numerical analysis for a simplified form of the Navier-Stokes equation for eccentric laminar capsule flow. The velocity ratio and pressure ratio $(\Delta P/L)_c/(\Delta P/L)_f$ were related to the friction factor as a function of the relative displacement of the capsule, which was defined as the rate of the displacement of the capsule axis from the pipe axis to the difference between the pipe and capsule radii. Good agreement with the experimental results was reported.

In part 9 of the ARC series, Kruger et al (11), in another analysis for eccentric laminar capsule flow in horizontal pipelines, introduced another parameter called the theoretical clearance C, which represented the minimum clearance between pipe wall and capsule. By analyzing the previous experimental results they established an expression to predict the value of C, from which the eccentricity ε of the capsule could be calculated from the equation

$$\varepsilon = 1-K-2C \tag{2.9}$$

where ε is the eccentricity. It is then possible to predict the values for the velocity ratio R_V and pressure ratio R_p by substituting ε into the following equations

$$R_v = \frac{V_c}{V_{av}} = \frac{Q_C}{K^2(Q_C+Q_A)} \text{ and}$$

$$R_p = \frac{(\Delta P/L)_c}{(\Delta P/L)_f} = \frac{Q_P}{(Q_C+Q_A)}$$

where $Q_C = B(\Delta P/L)_c\ f_1(k,\varepsilon)$ (volumetric flowrate of capsule)

$Q_A = B(\Delta P/L)_c\ f_2(K,\varepsilon)$ (volumetric flowrate of annulus)

$Q_P = B(\Delta P/L)_f$ (volumetric flowrate of pipe)

and B is a constant.

Although the developments of both analyses were of significance for some of the flow phenomena in laminar flow, the fact that they were not generalized and lacked simplicity had limited their applications to more general cases.

After clarifying the effects of the more pertinent parameters on capsule flow, the latter part of the research at the ARC was directed towards obtaining correlations for predicting capsule velocity and pressure gradient (12, 31) and to generating information or equations for the design of capsule pipeline systems (28, 30-32, 35-37). They claimed that capsule pipeline systems could be designed and built with complete confidence (26).

The present study is concerned with capsule flow in a vertical pipeline, for which no information was available. Consequently, any data related to vertical pipelines was considered, such as that of stationary bodies in vertical tubes or pipes. The following part of this chapter is a review on this aspect but is confined to research which used high Reynolds number flow.

The earliest study concerning the variation of drag coefficient for stationary spheres in fluid flow in a bound medium at high Reynolds number was that of McNown and Newlin (1). The spheres that they used were rigidly mounted in a tube with uniform air flow with a Re in the range 10^4 - 10^5. They arrived at the following analytical relationship:

$$C_d = \left[\frac{d/D}{1-(d/D)^2}\right]^2 \qquad (2.9)$$

which neglects the viscous effect, but still closely related to their experimental data especially at d/D > .80.

Following McNown and Newlin, Young (2) Richhorn and Small (45) carried out similar studies. The spheres in these experiments were freely suspended and the tube was inclined to accommodate the need for data for the spheres at different radial displacements, while at the same time being free of frictional effect.

Round et al (17, 18) carried out two experiments on the suspension of single sphere in water and in air in tubes of various diameters and in various angles of inclination. The angle of inclination of the tubes to the horizontal was varied from 0^o to 90^o. Measurements were made to determine the liquid velocities required to support the spheres and the pressure drops associated with these velocities. In both experiments they observed that at an angle of inclination between 20-65^o, the spheres became still at suspension, but at an angle near to 90^o the spheres were unstable and bouncing from side to side in the tube. For the spheres at still suspension they showed that the drag coefficient of a given sphere was constant. In the second part of the experiment they presented two correlations:

a) The velocity function:

$$\frac{(V_{av})^2}{Dg(\sigma-\rho)/\rho \sin \theta} = \frac{2}{3K} d/D[1-(d/D)^2] \qquad (2.10)$$

b) The pressure function:

$$\frac{\Delta P_m - \Delta P_L}{(\sigma-\rho)D \sin \theta} = \frac{2}{3}(d/D)^3 \qquad (2.11)$$

where K is a modified form of the drag coefficient which was determined by substituting 0.54 for the L.H.S. and d/D = 0.47 into Equation (2.10). These values correspond to the maximum condition in the plot of the non-dimensional velocity function versus d/D.

Since 1969, the department of Mechanical Engineering at McMaster University has been actively involved on the research of stationary and dynamic capsules in pipelines.

The initial research was that of Tawo (19) who studied the pressure gradient for sphere trains rigidly fixed to the inside wall of a horizontal pipe with water flowing at Reynolds number ranging from 10^4 to 10^5. The pressure drop measurements were correlated as a function of diameter ratio and Reynolds number.

Experiments performed thereafter were carried out in a vertical pipeline using both water and aqueous polymer solution as the working fluid.

The use of polymer solution was to study the phenomenon of drag reduction additives on the system.

Latto et al (20, 21) carried out the first experiment in the vertical pipeline to investigate the hydrodynamic suspension of single sphere and sphere train in water and polymer solution. Steel and lucite spheres with d/D ranging from 0.29 to 0.95 were used. Measurements of suspension velocity and pressure drop were made. Results obtained from the measurements for various concentrations were compared to that for water. It was found that the drag coefficient was not affected by the addition of polymer solution for diameter ratios $d/D > 0.7$. They established a semi-empirical equation for the pressure drop associated with the capsule at hydrodynamic suspension as a function of d/D in the form

$$\frac{(\Delta P_m - \Delta P_L)}{(\sigma - \rho) D \sin \theta} = 0.633 (d/D)^{2.94} \qquad (2.12)$$

which was in good agreement with the data for air and water.

The next work in the series was that of Aly (22), Latto et al (38) who extended the study to include cylinder train with diameter ratios ranging from 0.45 to 0.9. They showed that for nylon spheres and cylinders the drag coefficients approached a constant value as L/d was increased, and that the drag coefficient per (L/d) for cylinder train was smaller than that per unit sphere of an equivalent sphere train. Semi-empirical equations similar to that of Latto's (Eqn. 2.12) were derived.

$$\frac{\Delta P_m - \Delta P_L}{D(\sigma - \rho) g} = 0.79 (d/D)^{3.572} \, n^{1.003} \quad \text{(sphere train)} \qquad (2.13a)$$

$$\frac{\Delta P_m - \Delta P_L}{D(\sigma - \rho) g} = 0.933 (d/D)^{3.438} (L/d)^{1.099} \quad \text{(cylinder train)} \qquad (2.13b)$$

Latto and Lee (23, 24) extended the research to include the effect of modified end shapes on drag coefficient and pressure drop. They showed that significant pressure drag reduction was achieved by the addition of a hemisphere nose cape.

Alnakeeb (41) performed the study on the drag coefficient for tethered spheres in the same vertical pipeline with and without polymer addition. The diameter ratios were ranged from 0.439 to 0.87. Semi-empirical correlations were obtained for the drag coefficient and the pressure function in the range of tube Reynolds number of 3.9×10^3 to 9.2×10^4. In the experiments using Reten 423 polymer solution, it was found that a maximized drag reduction occurred at concentration of about 24 wppm for sphere of $d/D > 0.74$, and that higher drag reduction was achieved for tethered spheres than for untethered ones.

CHAPTER 3

THEORY

In order to model the capsule-pipeline system, it is necessary to obtain relationships between capsule velocity, the pressure gradients across the capsules and the physical variables of the system. The following approaches were adopted to achieve this:

I <u>Dimensional Analysis</u>:

One of the main objects of the research was an investigation of the individual effects of various non-dimensional parameters on the variation of capsule velocity and pressure gradient. These dimensionless parameters can be established using the following dimensional analysis.

Considering a rigid cylindrical capsule of any size and density flowing under the influence of a liquid carrier in a pipeline, it is possible to write:

$$V_c \text{ or } (P/L)_c = F_1(V_{av}, \mu, \rho, \sigma, L, d, D, e_c, e_p, \text{endshape}) \quad (3.1)$$

If M, L, T are chosen as the fundamental dimensions and V_{av}, ρ, D are as the repeating variables, then the variables in Equation (3.1) may be related by 8 dimensionless groups or π terms as follows:

$$\pi_1 = (V_{av}^a D^b \rho^c) V_c \text{ or } (\Delta P/L)_c$$

$$\pi_2 = (V_{av}^a D^b \rho^c) \mu$$

$$\pi_3 = (V_{av}{}^a D^b \rho^c)\sigma$$

$$\pi_4 = (V_{av}{}^a D^b \rho^c)d$$

$$\pi_5 = (V_{av}{}^a D^b \rho^c)L$$

$$\pi_6 = (V_{av}{}^a D^b \rho^c)\ell_c$$

$$\pi_7 = (V_{av}{}^a D^b \rho^c)\ell_p$$

π_8 = end shape

For dimensional homogenity the solutions are:

$$\pi_1 = V_c/V_{av} \quad \text{or} \quad (\Delta P/L)_c \frac{D}{\rho V_{av}{}^2}$$

$$\pi_2 = \frac{\rho V_{av} D}{\mu}$$

$$\pi_3 = \frac{\sigma-\rho}{\rho}$$

$$\pi_4 = d/D$$

$$\pi_5 = L/D$$

$$\pi_6 = \ell_c/d$$

$$\pi_7 = \ell_p/D$$

π_8 = end shape

where $(\Delta P/L)_c \frac{D}{\rho V_{av}{}^2}$ can be written as

$$(\Delta P/L)_c\left[\frac{1}{f(L/D)(1/L)\frac{\rho V_{av}{}^2}{2}}\right] \quad \text{or} \quad (\Delta P/L)_c/(\Delta P/L)_L,$$

which is the ratio of pressure gradient across the capsule to that of the free pipe.

Equation (3.1) then becomes:

$$\frac{V_c}{V_{av}} \text{ or } \frac{(\Delta P/L)_C}{(\Delta P/L)_L} = F_2\left(\frac{\rho V_{AV} D}{\mu}, \frac{\sigma-\rho}{\rho}, \frac{d}{D}, \frac{L}{d}, \frac{\ell_c}{d}, \frac{\ell_p}{D} \text{ endshape}\right)$$

The analysis for the case of a spherical capsule would give the same dimensionless groups except that $\pi_5 = L/d = 1$ for a single sphere of which the significant length would be d.

Since the present experiments are limited to a single liquid in one pipe diameter, the Reynolds number, $\frac{\rho V_{av} D}{\mu}$ is proportional to V_{av}, and ℓ_p/D could not be varied. If the relative roughness ℓ_c/d for all the capsules was maintained constant throughout the experiments then the independent variables that could be investigated are:

$$V_c/V_{av} \text{ or } \frac{(\Delta P/L)_C}{(\Delta P/L)_L} = F_2\left(V_{av}, \frac{\sigma-\rho}{\rho}, d/D, L/d\right)$$

(cylinders) (3.2)

$$V_c/V_{av} \text{ or } \frac{(\Delta P/d)_C}{(\Delta P/d)_L} = F_2\left(V_{av}, \frac{\sigma-\rho}{\rho}, d/D\right)$$

(spheres) (3.3)

II General Analysis

1) Overall Continuity Considerations:

Consider the control volume as depicted in Figure (3.1). Mass continuity requires that:

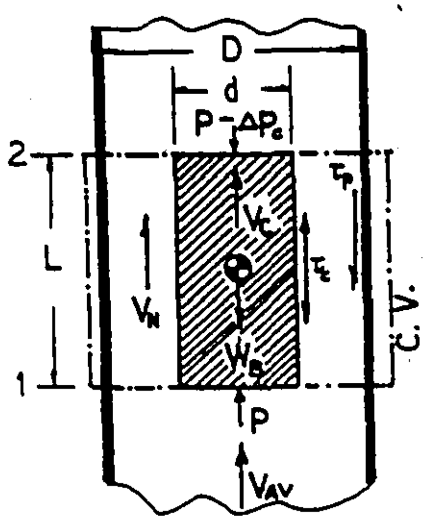


FIG.(3.1): SCHEMATIC OF THE CONTROL VOLUME IN THE TEST SECTION

$$Q_C + Q_N = Q_{av}$$

$$\text{or} \quad V_N \frac{\pi(D^2-d^2)}{4} + V_c \frac{\pi d^2}{4} = V_{av} \frac{\pi D^2}{4}$$

$$V_N(1-K^2) + K^2 V_c = V_{av}$$

$$V_N - V_c = \frac{V_{av}-V_c}{1-K^2} \qquad (3.4)$$

2) Capsule Flow Mechanism:

Consider a free cylindrical capsule at rest or in steady motion in a vertical pipeline with a flowing carrier fluid. The free flow of the capsule is governed by the various forces acting on it. These forces are summarized in Figure (3.1) as:

i) The buoyed weight of the capsule acting vertically downward, W_B.

ii) The pressure forces in the liquid acting perpendicular to the capsule surface at every point, F_p.

iii) The shear force due to the liquid acting at each point tangentially to the capsule surfaces, F_s.

iv) The forces due to the pipe wall such as the drag forces due to the friction between the capsule and the pipe wall when the capsule is travelling in contact with the pipe wall. There is also shear force in the fluid due to friction of the pipe wall; this force might not directly affect the capsule velocity but it would affect the pressure gradient.

All these forces may be resolved into transverse and longitudinal components with respect to the axis of the pipe.

The longitudinal component of the forces consists of a pressure force acting at the ends of the capsule and the shear force acting at the side of the capsule. The pressure force always exerts a thrust force on the capsule while the shear force may exert a thrust or a drag force on the capsule. The shear forces considered here are restricted to these due to the fluid or viscous shear forces.

The component of drag force due to the contact of the capsule with the pipe wall should not affect the general analysis since for a vertical pipeline the cylinder is not generally in contact with the pipe wall.

The transverse component of the forces consists of pressure force acting on the sides and the shear force acting parallel to the ends of the capsule. Since there is essentially no flow from side to side the pressure force on each side is equal. The shear forces on the ends of the capsule will be small compared with those on the sides, and in any case will tend to cancel out as regards to their parallel and perpendicular components.

Therefore it is the longitudinal component of the pressure force and the shear force that contribute to the motion of the capsule. The summation of these forces is always equal to the buoyed weight of the capsule when the capsule is hydraulically suspended or travelling at steady velocity, that is,

$$F_p \pm |F_s| = W_B \qquad (3.5)$$

where F_p is the thrust due to the parallel component of the pressure force.

F_s is the thrust due to the parallel component of the shear force.

W_B is the buoyed weight of the capsule.

The liquid velocity which is just sufficient to suspend the capsule is called the "suspension velocity", V_o. If the liquid velocity is increased above that of V_o the capsule begins to move at a constant velocity after an initial acceleration. When the capsule is at steady motion, the total thrust can be no greater than before the increase of liquid velocity since the buoyed weight of the capsule is constant. However, the pressure forces will have increased with the increase of liquid velocity, so that the thrust due to the shear force will necessarily have decreased. This latter result can only be brought about by a decrease of the average liquid velocity in the annulus relative to the capsule, i.e. $(V_N - V_C)$, since the shear force increases or decreases with this quantity. A decrease of $(V_N - V_C)$ for a given V_{av} means an increase of V_C. Therefore, the effect of increasing V_{av} is to increase V_C.

When the water velocity is further raised to a value such that $(V_N - V_C) < 0$, the shear force is then opposing the capsule motion and acting as a negative component of the thrust force. According to Equation (3.4), a negative value of $(V_N - V_C)$ will give a value of V_C/V_{av} greater than unity. Hence, a negative sign to the absolute value of F_s in Equation (3.5) is added to take into account of the case where $V_C/V_{av} > 1$.

3) <u>Force and Momentum Balance</u>:

In conjunction with the analysis just described, two considerations, which are probably more useful in practical applications, based upon simple overall force balance and momentum balance may be established as follows:

3.a) <u>Force Balance</u>:

<u>For Capsules at Suspension</u>: Considering the control volume as depicted in Figure (3.1), the force balance on the capsule is given by Equation (3.5), that is

$$\text{total thrust} = \text{buoyed weight} \qquad (3.6)$$

For a cylindrical capsule it is

$$C_d^* \frac{\rho V_o^2}{2} \frac{\pi d^2}{4} = (\sigma - \rho) g L \frac{\pi d^2}{4}$$

$$C_d^* = (S_c - 1) \frac{2gL}{V_o^2} \quad \text{(cylinder)} \qquad (3.7)$$

For a single spherical capsule it is

$$C_d^* = (S_c-1)\,\frac{4}{3}\,\frac{gd}{V_o^2} \qquad \text{(sphere)} \qquad (3.8)$$

where C_d^* is the overall drag coefficient

V_o is the suspension liquid velocity

If the average local liquid velocity in the annular spacing between the capsule and the pipe wall is used instead of the average liquid velocity in the free pipe, then according to Equation (3.4) with $V_c = 0$

$$V_N = \frac{V_o}{(1-K^2)},$$

alternative forms of the drag coefficient can be defined by:

$$C_d^{**} = (S_c-1)\,\frac{2gL}{V_o^2}\,(1-K^2)^2 \qquad (3.9)$$

$$C_d^{**} = (S_c-1)\,\frac{4}{3}\,\frac{gd}{V_o^2}\,(1-K^2)^2 \qquad (3.10)$$

Rearranging Equation (3.9) and (3.10) gives

$$V_o = [2gD(S_c-1)(L/d)(d/D)]^{\frac{1}{2}}(1-K^2)/\sqrt{C_d^{**}} \qquad \text{(cylinder)} \qquad (3.11)$$

$$V_o = [\tfrac{4}{3}g(S_c-1)(d/D)]^{\frac{1}{2}}(1-K^2)/\sqrt{C_d^{**}} \qquad \text{(sphere)} \qquad (3.12)$$

It is seen from the above two equations that the suspension velocity of a given capsule in a given pipeline may be calculated if the drag coefficient C_d^{**} could be determined. Theoretically, for a capsule of given material, C_d^{**} varies with L/d, d/D and V_{av}. But since V_{av} varies implicitly with L/d and d/D, C_d^{**} is in turn a function of L/d and d/D only. Hence, Equations (3.11) and (3.12) may be written as:

$$V_o = \sqrt{2gD(S_c-1)}\,(1-K^2)(L/d)^a(d/D)^b \qquad \text{(cylinder)} \qquad (3.13)$$

$$V_o = \sqrt{\tfrac{4}{3}gD(S_c-1)}\,(1-K^2)(d/D)^c \qquad \text{(sphere)} \qquad (3.14)$$

where a, b or c are empirically determined constants.

These two semi-empirical relationships will be incorporated with the actual average liquid velocity V_{av} in the establishment of the correlation between liquid velocity and capsule velocity.

<u>For Capsules at Steady Motion</u>: Under this condition, Equation (3.6) is still applicable but instead of using V_o as in the suspension case, a relative velocity has to be used. If $(V_{av} - V_c)$ is used, then

$$C_{d_2} = (S_c-1)\,\frac{2gL}{(V_{av}-V_c)^2}$$

or

$$C_{d_2} = (S_c-1)\,\frac{2gL}{V_{av}^2}\,\left[\frac{1}{(1-\frac{V_c}{V_{av}})^2}\right]$$

$$C_{d_2} = C_{d_1}\left[\frac{1}{(1-V_c/V_{av})^2}\right] \qquad (3.15)$$

where $C_{d_1} = (S_c-1)\,2gL/V_{av}^2$

If the annular average water velocity relative to the capsule velocity, $(V_N - V_C)$, is used then according to Equation (3.4)

$$C_{d_3} = (S_c - 1)\,\frac{2gL}{(V_N - V_c)^2}$$

or

$$C_{d_3} = (S_c - 1)\; 2gL \left[\frac{(1-K^2)}{(V_{av} - V_c)}\right]^2$$

$$C_{d_3} = C_{d_2}(1-K^2)^2 \qquad (3.16)$$

Equations (3.15) and (3.16) are both applicable to spheres except that for spheres $C_{d_1} = (S_c - 1)\frac{4}{3}\,\frac{gd}{V_{av}^{\;2}}$

3.b) <u>Momentum Balance</u>:

Again the control volume in Figure (3.1) is considered, momentum conservation requires that

$$P_1A_1 + (\rho UA)_1U_1 = P_2A_2 + (\rho UA)_2 + \tau_p\pi DL + \frac{\pi}{4}(D^2 - d^2)L\rho g + \frac{\pi d^2}{4}L\sigma g \qquad (3.17)$$

For steady-state incompressible flow in one-diameter pipe,

$$A_1 = A_2; \quad U_1 = U_2; \quad \rho_1 = \rho_2$$

Hence Equation (3.17) becomes

$$\Delta P_m = \frac{4\tau_p L}{D} + (d/D)^2\, L(\sigma - \rho)g + \rho L g \qquad (3.18)$$

Now consider the same control volume with no capsule present in it but with fluid alone flowing at the same velocity, the same consideration will give

$$\Delta P_L = \frac{4\tau_p' L}{D} + \rho L g \qquad (3.19)$$

Subtracting Equation (3.18) from Equation (3.19) gives

$$\Delta P_m - \Delta P_L = L(d/D)^2(\sigma-\rho)g + \frac{4L}{D}(\tau_p - \tau_p') \quad (3.20)$$

Here τ_p is not necessarily equal to τ_p' since the velocity profile in the annulus is not the same as that in the free pipe, but as a first step, an approximation of $\tau_p = \tau_p'$ is assumed to get the following relationship:

$$\Delta P_m - \Delta P_L = L(d/D)^2(\sigma-\rho)g \quad (3.21)$$

Because it is assumed that $\tau_p = \tau_p'$, the results computed from Equation (3.21) might deviate from the experimental results. To allow for this descrepancy, an empirical correlation may have the form as follows:

$$\frac{\Delta P_m - \Delta P_L}{L(\sigma-\rho)g} = C(d/D)^P$$

or

$$\frac{(\Delta P_o/L)_c}{(\sigma-\rho)g} = C(K)^P \qquad \text{(cylinder)} \quad (3.22)$$

where $(\Delta P_o/L)_c = (\Delta P_m - \Delta P_L)/L$ ——— the pressure gradient across the capsule due to the capsule alone, and C, P are universal constants.

Similar correlation can be obtained for spherical capsules i.e.

$$\Delta P_m - \Delta P_L = 2/3\ d(d/D)^2(\sigma-\rho)g$$

or

$$\frac{\Delta P_m - \Delta P_L}{d(\sigma-\rho)g} = 2/3\ (d/D)^2 \quad (3.23)$$

$$\text{or} \quad \frac{(\Delta P_o/d)_c}{(\sigma-\rho)g} = C'(K)^{p'} \qquad \text{(sphere)} \qquad (3.24)$$

The above pressure analysis can be applied to both cases where $V_c = 0$ or $V_c \neq 0$.

CHAPTER 4

APPARATUS AND EXPERIMENTAL PROCEDURE

PART 1 - APPARATUS

The apparatus was specifically designed for the present study such that it satisfies the following special requirements for the study of moving capsules.

1) The overall system: should be relatively simple such that it can be controlled by a single operator.

2) The flow system: should be sufficiently rigid to withstand impacts and vibration produced by the pump and the moving capsule, and provide a range of flow velocities from 0 to 6 m/s with sufficient pressure head for the transport of aluminum capsules of d/D up to 0.85 and L/d=14.

3) Measurement systems: All the measurement devices should have relatively high precision and fast response with continuous recording where necessary to give an overall accuracy of approximately 5%.

Detailed discussion of various aspects of the system are presented under separated headings as follows:

4.1 The Flow System

A schematic of the entire system is shown in Figure (4.1) with the main components shown in an insert photograph

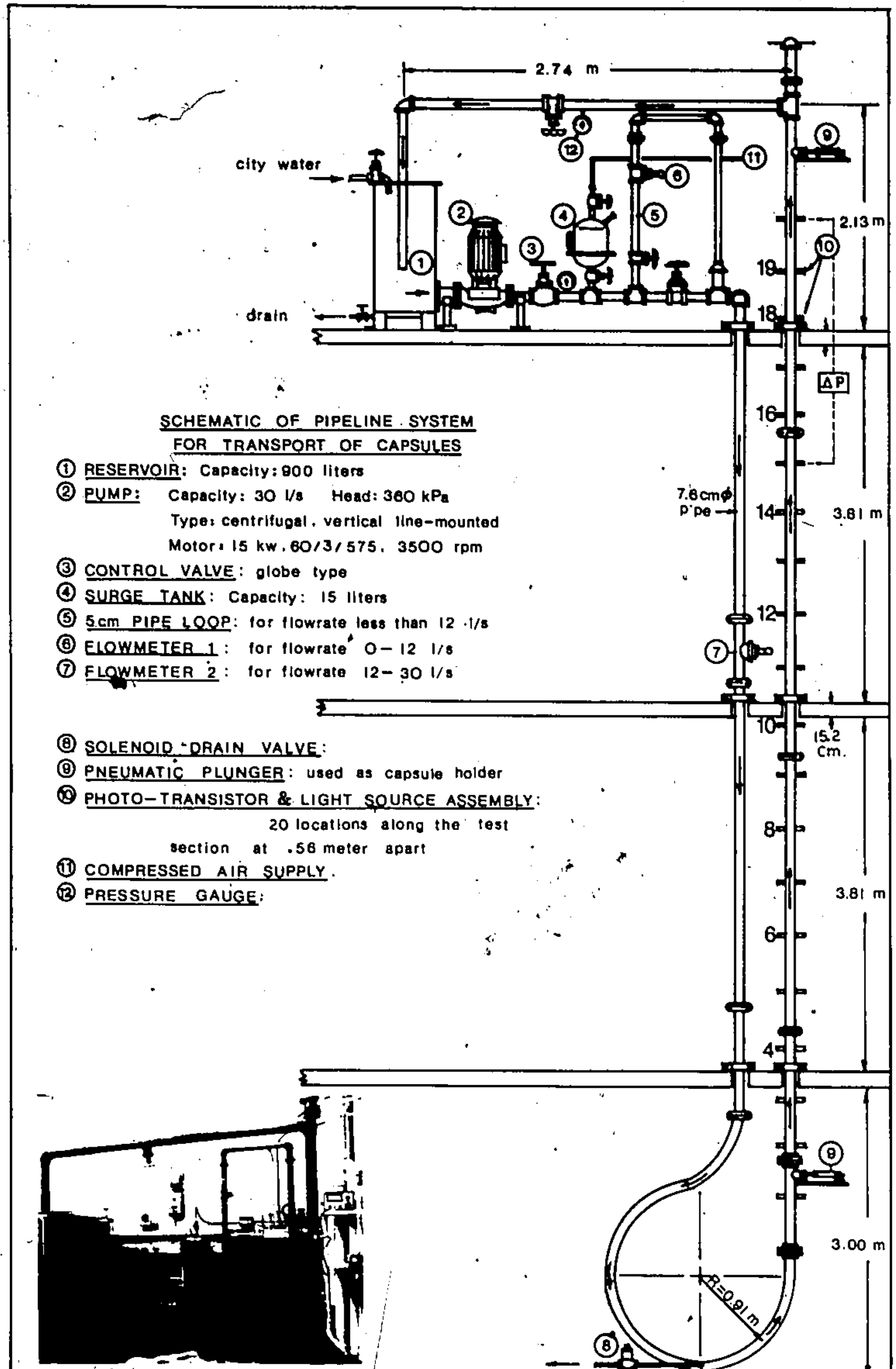

SCHEMATIC OF PIPELINE SYSTEM
FOR TRANSPORT OF CAPSULES
① RESERVOIR: Capacity: 900 liters
② PUMP: Capacity: 30 l/s Head: 360 kPa
Type: centrifugal, vertical line-mounted
Motor: 15 kw, 60/3/575, 3500 rpm
③ CONTROL VALVE: globe type
④ SURGE TANK: Capacity: 15 liters
⑤ 5cm PIPE LOOP: for flowrate less than 12 l/s
⑥ FLOWMETER 1: for flowrate 0 – 12 l/s
⑦ FLOWMETER 2: for flowrate 12 – 30 l/s
⑧ SOLENOID DRAIN VALVE:
⑨ PNEUMATIC PLUNGER: used as capsule holder
⑩ PHOTO-TRANSISTOR & LIGHT SOURCE ASSEMBLY:
20 locations along the test section at .56 meter apart
⑪ COMPRESSED AIR SUPPLY.
⑫ PRESSURE GAUGE:
2.74 m
city water
drain
2.13 m
ΔP
7.6cmφ pipe
3.81 m
15.2 cm.
3.81 m
3.00 m
R=0.91 m
19
18
16
14
12
10
8
6
4

Figure (4.1)

at the left lower corner.

4.1a) <u>The Flow Path</u>: This apparatus is basically a recirculating flow system with the flow direction as shown by the arrows in Figure (4.1). The water in the reservoir is discharged to a horizontal pipe section by the centrifugal pump. Upon leaving the pump the flow is first regulated to the desired flowrate by the globe valve, and then passes by a surge tank which dampens any flow fluctuations. The flow then passes through either the 5 cm I.D. by-pass loop or continues along the horizontal line to a 9 meter long vertical section. A 1.82 meter diameter circular bend at the basement redirects the flow upward through the vertical test section back to the reservoir.

4.1b) <u>The Pipework</u>: The entire pipe loop is of 40-schedule steel pipe of 7.6 cm I.D. for the main loop and 5 cm I.D. for the by-pass loop. The steel pipe provides the necessary rigidity and strength to the system to withstand the stress created by the pump and the impact of the moving capsules. The vertical sections consisting of various lengths of pipe are assembled together with Victaulic couplings to provide smooth and flexible connections which were necessary for the alignment of the test section. Each pipe section, when passing through a floor, is supported by a pipe bracket resting on the floor, such that individual assembly or disassembly of any of these sections is permitted.

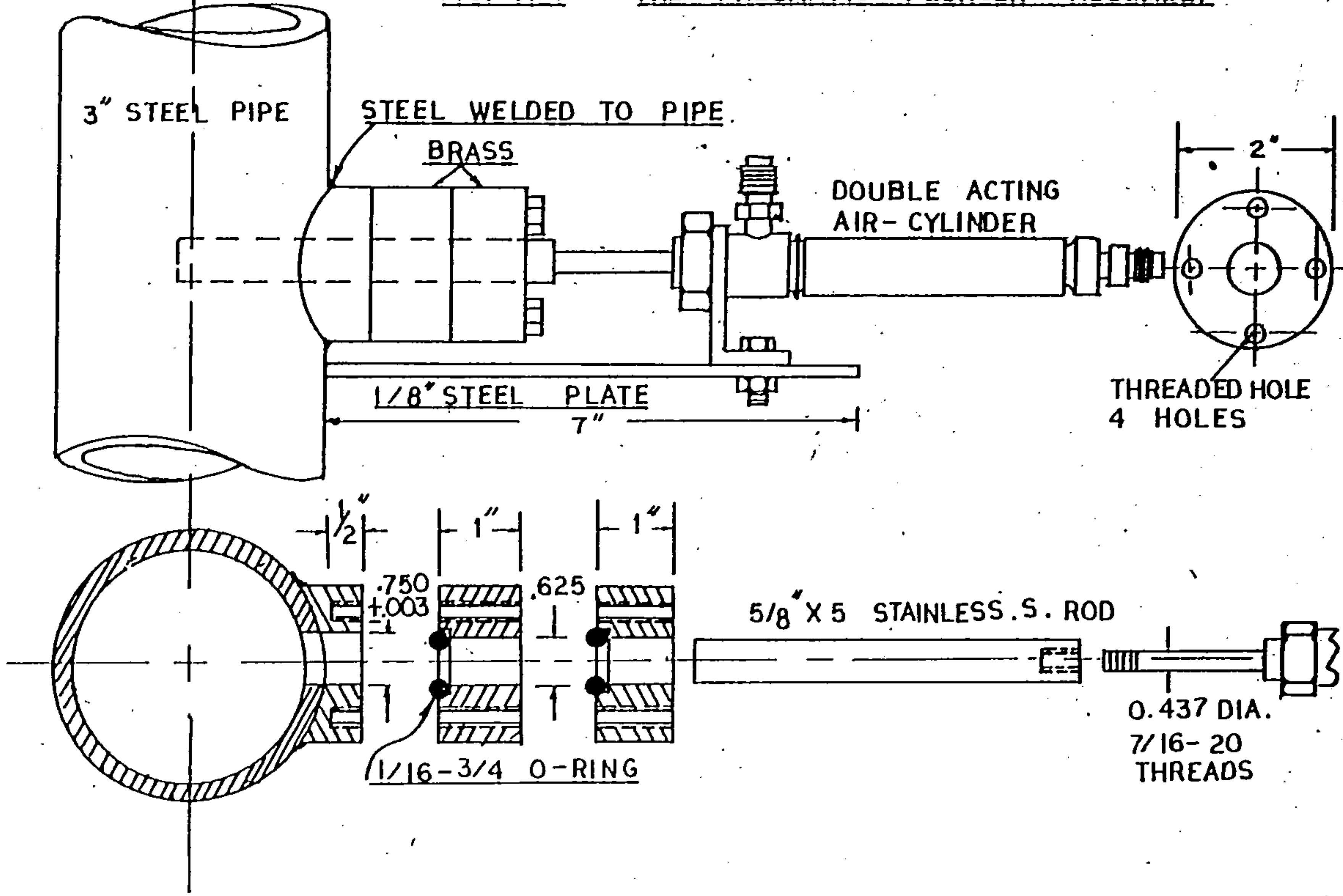
4.1c) The Reservoir: The reservoir is made of aluminum and has a capacity of 900 litres (dimension of .61x1.22x1.22 m). A 2.54 cm I.D. city water supply line and a drain line, both equipped with a gate valve, are installed respectively on top and at the bottom of the reservoir. During a normal run these two valves were frequently adjusted to maintain at constant head and temperature of the water in the reservoir.

4.1d) The Pump: The centrifugal pump powered by a 15 Kw and 3500 RPM electric motor can deliver a flowrate up to 30 litre/sec at 360 kPa pressure head. The corresponding maximum flow velocity and Reynolds number in the pipeline are 6.4 m/s and 5×10^5 respectively.

4.1e) The Surge Tank: The surge tank, having an effective volume of 15 litres, is fitted with two globe valves which are located in the connections to the main loop and to the compressed air supply line respectively. Fluctuations associated with the flow are damped by adjusting these two valves.

4.1f) The By-Pass Loop: A by-pass loop is needed because the flowmeter located at the main loop has a limited range of 12-30 litres. For a flowrate less than 12 l/s, the flow is passed through the smaller flowmeter located in the by-pass loop. Two gate valves located at the entrance to each of these loops can be adjusted to direct the flow

FIG.(4.2) : THE PNEUMATIC PLUNGER ASSEMBLY



through an appropriate path in accordance with the flow range. At the entrance to the by-pass loop a fine honeycomb filter is fixed to homogenize the flow and reduce the effects of the bend.

4.1g) <u>The Test Section</u>: The 11 meters long vertical portion on the return side of the flow system, starting from the first pneumatic plunger located just after the main bend, is designated as the "Test Section". At the top of the test section, the pipe is capped, which permits the insertion and removal of a capsule. A "Tee" piece, which has a perforated sleeve in it, located just 1/2 meter below the cap allows the flow to return to the reservoir.

Twenty pairs of adjacent holes having pipe threads to fit 1.27 cm standard brass nipples are located at equal distance up the pipe wall on opposite sides along the test section. These are the locations of phototransistors and light sources for measuring the capsule velocities.

4.1h) <u>The Pneumatic Plungers</u>: Two pneumatically actuated plungers (see Figure (4.2) for detail construction), located at the entrance to the test section and a short distance below the outlet tee, are used to restrain the capsules. The top plunger, which was later replaced by a steel rod in a swagelock fitting, is used for insertion or removal of capsules. The lower plunger is used for restraining the capsule at the bottom of the test section while the flowrate or flow equilibrium is being established.

4.1i) Miscellaneous: (1) Back pressure gate valve: This is installed in the horizontal return pipe above the reservoir to regulate the flow and consequently the back pressure to the sytem and ensure that it is higher than the atmospheric pressure. A back pressure of 5 psi was usually maintained for every flowrate . (2) Pressure gauges: Two pressure gauges, one located immediately after the pump and the other in the return pipe before the back pressure gate valve, are used for indicating the supply and the back pressure of the flow. (3) Solenoid drain valve: This is located at the bottom of the 1.81 m-diameter circular loop for draining the pipeline.

4.2 Measurement System

The quantities to be measured in the experiments are: flow velocity, capsule velocity, pressure drop and temperature and consequently four sub-systems were designed to accommodate these measurements.

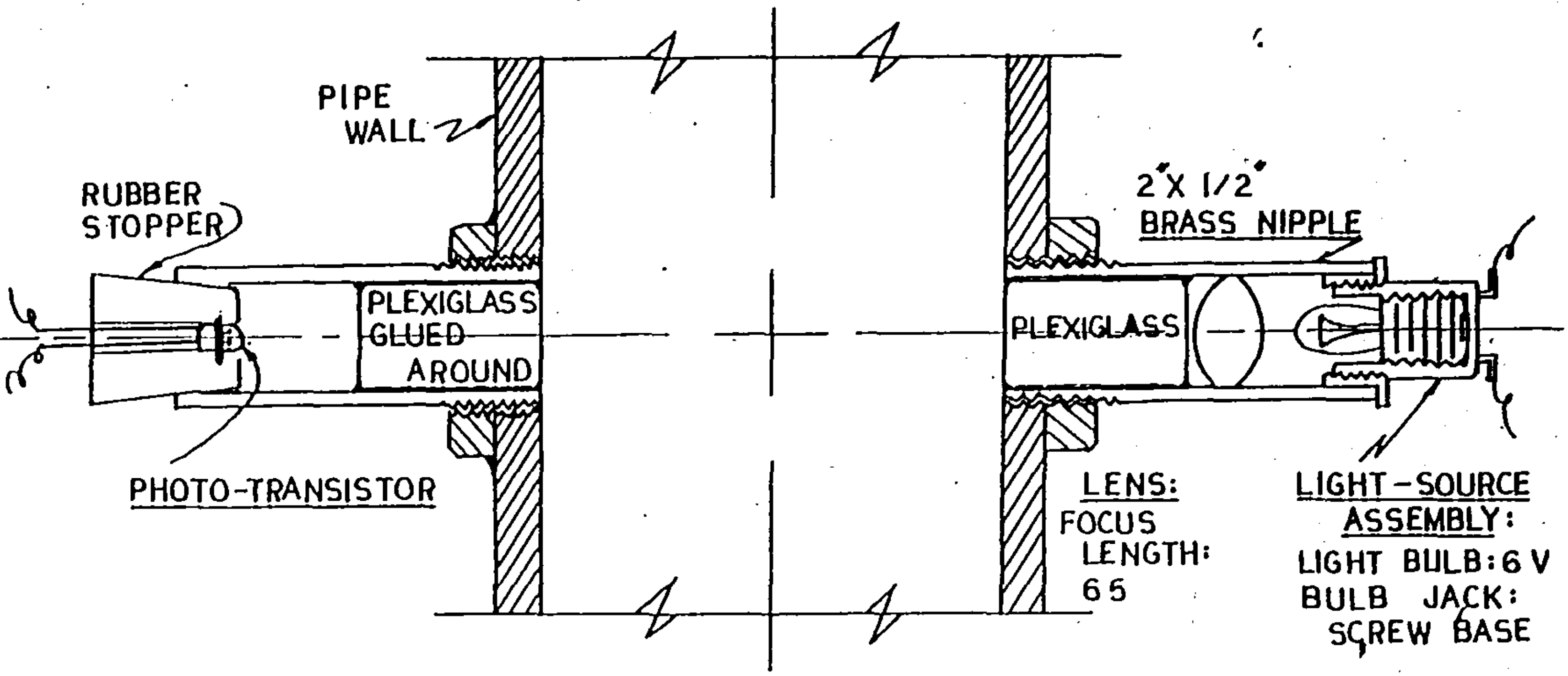
4.2a) Flow measurement system: It consists of two Signet MK315 paddle wheel flowsensors, a Signet MK365 digital display flowmeter and a "Rikadenki" chart recorder. The flow sensors, which are located in the by-pass loop to cover the range of 0-12 l/s and in the main loop to cover the range of 12-30 l/s, are inserted through special fittings into the pipeline with their wheels axes perpendicular to that of the pipe. The rotation of the wheels created by the flow produces pulses or beats which are sent to the readout devices. The flowmeter has two channels each of which is pre-calibrated for a particular flowsensor. By selecting one channel at a time, the signals from the corresponding flowsensor are converted into USGPM and the result is displayed by the readout. The signals are pre-amplified into recordable voltage using a signet MK314 signal conditioner. Hence it is possible to obtain a continuous flow diagram for each test run by using a chart recorder. A typical flow diagram together with the pressure diagram is shown in Figure (4.5). The flowrate is determined by referring the average voltage, measured from the diagram, to the calibration curve (see Appendix [A]) for the corresponding flow range. All the flowrates which were used to calculate the average velocities (V_{av}) were determined in this way.

4.2b) Capsule Velocity Measurement System:

As mentioned in the description of the "Test Section", twenty equi-distant phototransistor-and-light-source (PL) locations are provided along the test section. This arrangement permits the measurement of the time required for a capsule to pass through an individual station or between any two stations. Hence the local velocities of the capsule along the test section can be determined on the basis of

FIG. (4.3): PHOTOTRANSISTOR & LIGHT-SOURCE ASSEMBLY

(TYPICAL ARRANGEMENT FOR TOTAL 22 LOCATIONS ALONG THE TEST SECTION)



either the capsule length or distance between stations. Not all the stations were used; only even numbers as marked in Figure (4.1) from #4 to #19 were equipped with PL units.

The construction of a PL unit is shown in Figure (4.3). The phototransistor and the light source, being contained separately inside two brass nipples, are installed adjacently to one another in the holes provided in the test section. When two of these PL units are connected to a time counter as shown in Figure (4.4), a measuring circuit is formed.

With this circuit both of the transistors are able to cause a voltage change across the individual resistors by disruption of their light sources. The change of voltage can either be used to start or stop the counter.

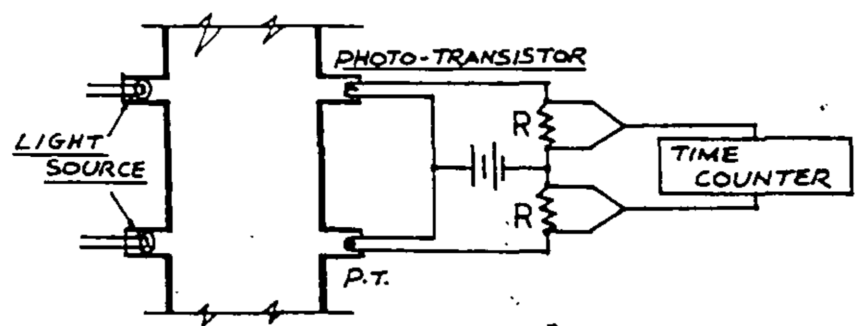


FIG. (4.4): CIRCUIT USED TO MEASURE V_C

The counter used was a Hewlett Packard 2-channel counter which had a sensitivity of 0.1 ms.

4.2c) <u>Pressure Measurement System</u>

The pressure drops due to the water flow and/or the capsule passage were measured by means of a diaphram type pressure transducer which was connected by using copper tubes between stations 15 and 20 (for cylinders with $L/d < 14$) or stations 15 and 18 (for $L/D = 14$). A "Rikadenki" chart recorder, also used for recording the flowrates, was used to record the pressure variation. The recorder was calibrated such that the reading from the chart was the value of the pressure in psi. A typical pressure diagram from the chart together with the flowrate diagram is shown in Figure (4.5). The pressure diagram consists of two parts: the pressure drop due to the fluid alone and that due to the capsule. When the fluid is stationary the pressure drop is zero. However when the fluid is flowing alone the total pressure drop due to pipe friction is shown by a rise in ΔP_L which is a function of the flow velocity. Furthermore when the capsule is present in the section between the pressure taps, a corresponding pressure drop of magnitude of ΔP_0 is measured. This pressure drop is a combination of the capsule buoyant weight, capsule friction loss and the pipe frictional loss.

From the pressure diagram, the pressure drops due to the capsule or the fluid or both are able to be determined.

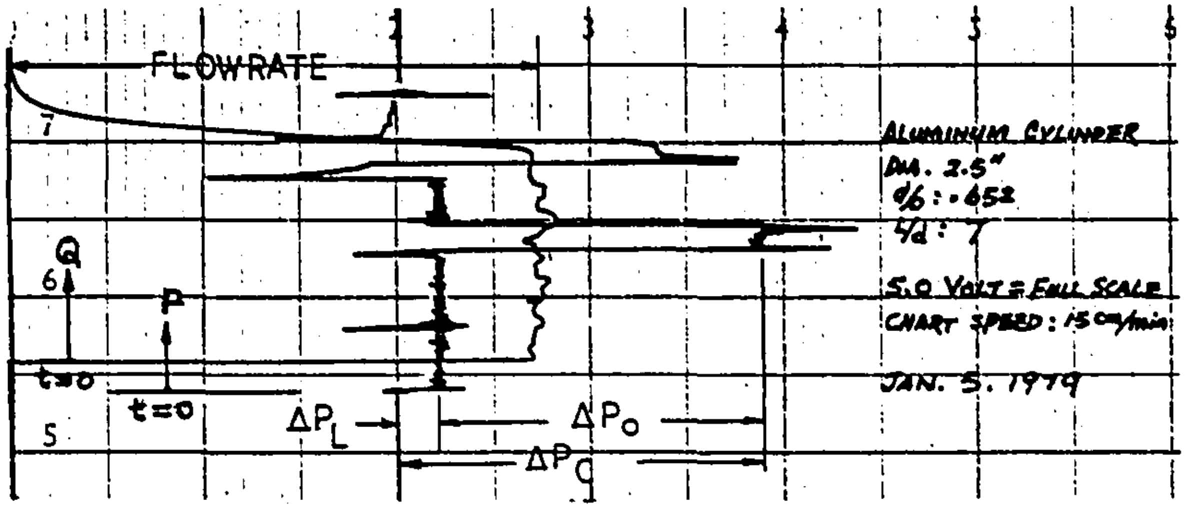


Figure (4.5) Flow and pressure diagram.

4.d) Temperature Measurement System:

Due to the internal friction the water temperature could rise by as much as 5^{o} C/hr when the system was in operation. Consequently, in order to achieve isothermal water conditions in the system it was necessary to, in most cases, add water from the cold main supply and continually bleed off to the drain. Therefore by careful control of the dilution and bleed off, water isothermal conditions could be maintained. A K-type thermocouple together with a read-out device was installed in the horizontal outlet pipe to indicate the water temperature. An arbitary value of 16^{o} C was used throughout the experiments.

4.3 Capsules:

The following capsules were used in the experiments:

4.3a) Spheres: Single spheres of nylon, aluminum and steel were investigated. Their specific gravity, size together with d/D ratio are listed in Table (4.1).

TABLE 4.1: Specifications of Spheres

Material	Specific Gravity S	Diameter (cm)	d/D
Nylon	1.15	4.445 ± .01	.57
Aluminium	2.7	5.08 ± .01	.652
Steel	7.82	6.35 ± .01	.815

4.3b) Cylinders: Only nylon and aluminum cylinders were used. The investigated diameter ratio (d/D) and aspect ratio (L/d) for both materials were: 0.489, 0.652, 0.815 and 4, 7, 10, 14 respectively, and Figure (4.6) shows the type of cylinder sections that were used. For a given diameter and material the cylinder lengths were varied by adding various basic lengths.

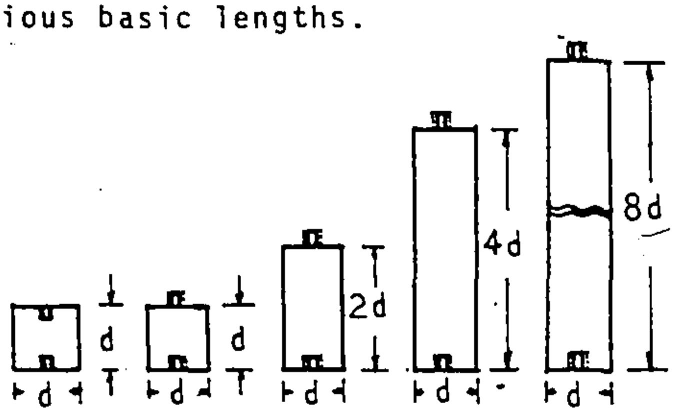


Figure (4.6) Cylinder sections for varying the length of a cylinder.

PART 2 - EXPERIMENTAL PROCEDURE

1) Preparation:

a) The Flow System: The reservoir was filled to two-thirds of its capacity with city water. Since the temperature was usually at 5 to 8° C, hot water was added to raise the temperature to about 16° C, the arbitary temperature set for these experiments. The pump was then started to circulate water in the pipeline for approximately 15 minutes to allow the system to reach thermal equilibrium. Since the water temperature rose gradually while the pump was running, both cold main water supply rate and the drainage rate from the reservoir were constantly adjusted to maintain the water in the system at 16° C. Meanwhile compressed air was supplied to the surge tank and the pneumatic plungers. The supply air pressure to the plunger was usually kept at 80 psi (552 kPa).

b) The Measurement Systems: All these systems were switched on sometime prior to the experimental runs to allow for warm-up. Checks were carried out to ensure that they were working properly. The time counter was connected to two consecutive PL-units stations via a control box. It was necessary to measure the local velocities of a capsule as it progressed up the test section for each flowrate, therefore each set of experimental runs for a given d/D and

L/d were done starting with the time measurement for the capsule to pass between the first two consecutive stations (i.e. #4 and #6). Then the experiment proceeded with the time between #6 and #8 and so forth.

c) Insertion of the Capsule: Insertion (or removal) of a capsule was done, with the pump stopped, through the top end of the test section. After removing the end cap located at the top end of the test section, the capsule to be investigated was inserted into the pipe and held up by the top plunger. After the cap was replaced, the capsule was released by withdrawing the plunger and allowed to drop to the bottom of the test section. Care was taken at this stage when using heavy capsules because system damage could be incurred in the free fall of the capsule. In order to avoid this the flow was started for a short while when the capsule nearly reached the bottom, which reduced the downward velocity of the capsule and prevented heavy impact by the capsule.

Once the capsule reached the bottom of the test section and it was held by the lower pneumatic plunger, experiment was ready to run.

Removal of the capsule was done in a reversed procedure. The capsule to be removed was pumped to the top of test section and was held by the top plunger. With the pump stopped and the pipe cap removed, the cylindrical capsule was removed by means of a threaded rod which was inserted into the threaded hole on the top end of the cylinder. The spheres were removed by means of a string trap.

2) Testing Procedure:

While the capsule was held at the bottom of the test section, the pump was started and the flow was regulated to a desired flowrate. The flowrates used were usually in the range from 5 to 22 ℓ/s with increments of 3.2 ℓ/s. The appropriate flow path was selected in accordance with the flowrate. For flow less than 12 ℓ/s, the by-pass loop was used, otherwise it was closed.

Once a flowrate was set and the flow stabilized, the capsule was released from the bottom of the test section and was allowed to pass to the top of the test section. The travelling time of the capsule, measured by the counter, between two selected stations was recorded.

When the capsule reached the top of the test section and was stopped at the outlet tee by the sudden change of flow direction, the pump was switched off and the capsule was allowed to fall back to the bottom of the test section using the previously described procedure. Once the capsule was back to position a "run" was completed.

Usually five runs were repeated, for a given capsule, for the time measurement for a given set of stations. However for the measurement of flowrate and pressure,only approximately five data records were taken for all the stations for the given capsule and flowrate.

Once the time measurements between all the sets of stations were completed, the procedure was repeated for the same capsule at a new flowrate. Usually 5 or more different flowrates were used for each capsule.

CHAPTER 5

RESULTS, CALCULATIONS AND DATA REDUCTION

Results:

The entire experimental data and calculated results are presented in tabular form in Appendix (D). The graphs based on these data and results are displayed in appropriate places with a general discussion in Chapter 6.

Calculation and Data Reduction:

1. The Average Water Velocity, V_{av}:

V_{av} was calculated according to the following equation:

$$V_{av} = \frac{\text{flow rate}}{\text{pipe cross-sectional area}}$$

$$= Q(USGPM)\left[\frac{\frac{1}{7.481}\times\frac{1}{60}\times 0.0283\ \text{GPM} \times m^3/s}{(0.078)^2\ \pi/4\ m^2}\right]$$

$$\therefore V_{av} = 0.0132 \times Q \quad (m/s) \qquad (5.1)$$

where Q is in USGPM and was calculated from either one of the following equations which were obtained from the calibration curves for the two flowsensors (see Appendix (A) for the calibration curves).

$$Q(USGPM) = 8+83.5\ V \qquad \text{(for 180-500 GPM)} \qquad (5.2a)$$

$$Q(USGPM) = 3.75+86\ V \qquad \text{(for 30-180 GPM)} \qquad (5.2b)$$

where V is the average voltage indicated on the individual flowrate diagram for the period being considered.

In the experiments the water flowrate was adjusted whilst the capsule was held stationarily by the lower plunger. In most cases the flowrates remained constant regardless of whether the capsule was in motion or stationary. However for high flowrates and/or when using larger capsules, it was found that the water flowrate, measured when the capsule was moving, was larger than the stationary capsule value. This variation in flowrate for larger capsules was expected since the system's hydraulic resistance was different thus affecting the pump output. For smaller capsules this effect was neglectable since the hydraulic resistance was not markedly changed. In order to calibrate the flow sensors, tests were carried out prior to the experiments to compare the flowrates with or without a capsule in the pipeline. It was found that, under the same valve setting, the measured water flowrate for a moving capsule was almost the same as that for no capsule present. Therefore the measured water flowrate for a moving capsule in the test section was considered to be the true flowrate and used when calculating the average water velocity for all the experiments.

2. <u>The Capsule Velocity</u>:

2.1) <u>The Local Capsule Velocity</u>: The velocity a capsule had attained when passing two stations was referred to as the local capsule velocity at that pipe section between the two stations, and was calculated according to the following equation:

$$V_c = \frac{\text{Distance between two stations}}{\text{Capsule passage time (Average of 5 readings)}}$$

$$V_c = \frac{(n_2 - n_1) \times 0.559}{t} (m/s) \quad (5.3)$$

where 0.559 m is the distance between two consecutive stations and n_1, n_2 are the pertinent upstream and downstream station numbers. The capsule passage time used in Equation (5.3) was the average value of five measurements from five repeated test runs for the same two stations. The time measurements were taken starting from station No. 4 and up along the test section at intervals of 1.118 meters. Usually six or more of such local velocity measurements were taken to obtain the velocity distribution along the test section for a given capsule at a given average water velocity.

2.2) <u>The Average Capsule Velocity,</u> $\overline{V}_c$: A capsule would usually attain a constant velocity, after an initial acceleration, which was taken as the average capsule velocity at that particular water flowrate. Sometimes a series of runs showed an inconsistency in this velocity which was due to the fluctuation of the time measurements. In such a case, the average value of the local velocities in a pipe section, in which the variation in the local velocities was less than $\pm 2\%$, was taken as the average capsule velocity.

3. <u>The Pressure Gradient Across Capsule</u>:

As mentioned in the section on "Pressure measurement system" in the previous chapter, all pressure drops were recorded in the form of pressure diagrams each of which consists of two parts: the pressure drop due to the fluid alone, and the pressure drop due to the capsule. The individual pressure gradients were hence:

$\Delta P_0/L_c$ - The pressure gradient due to the capsule

$\Delta P_L/L_p$ - The pressure gradient due to the fluid alone.

The sum of these two gradients is the total pressure gradient across the capsule, that is

$$(\Delta P/L)_c = (\Delta P_o/L_c) + (\Delta P_L/L_p)$$

where L_c and L_p are the length of the capsule and the distance between the pressure taps respectively. Two different values of L_p were used, they are:

$L_p = 2.79$ m for capsules of $L/d < 14$

$L_p = 1.68$ m for capsules of $L/d = 14$

As mentioned in the section on the "Average water velocity", the true water flowrate was that which was measured when a moving capsule was present. Hence the true pressure drop due to the fluid alone, ΔP_L was the value corresponding the true flowrate.

4. Others: The calculation of other variables such as d/D, L/d, $\overline{V}_c/V_{av}$, Reynolds numbers etc., were in accordance with the individual definition listed in the Nomenclature.

Sample Calculation:

A copy of a work sheet together with the corresponding flowrate and pressure drop diagrams is shown on Table (5.1).

The general information concerning the specific test are given below:

Material of the capsule: Aluminum

Specific gravity: S=2.7

Diameter: d=5.08 cm $d/D = \frac{5.08}{7.79} = 0.652$

Length: L=50.8 cm $L/d=\frac{50.8}{5.08} = 10$

Measurements from diagrams:

Voltage for flowrate: V = 2.65 V

Pressure drop due to capsule: $\Delta P_0 = 0.66$ psi

Pressure drop due to fluid: $\Delta P_L = 0.42$ psi

Calculations:

1) Local capsule velocity:

For example consider stations No. 8 - 10, the local capsule velocity in the pipe section between stations 6 and 8, according to Equation (5.3), is:

$$\ell V_c = \frac{(8-6)0.559}{0.8604} = 1.2994 \text{ m/s} = 4.2631 \text{ ft/sec}$$

2) Average capsule velocity:

By inspection all the local velocities it is found that the capsule attained a constant velocity after reaching

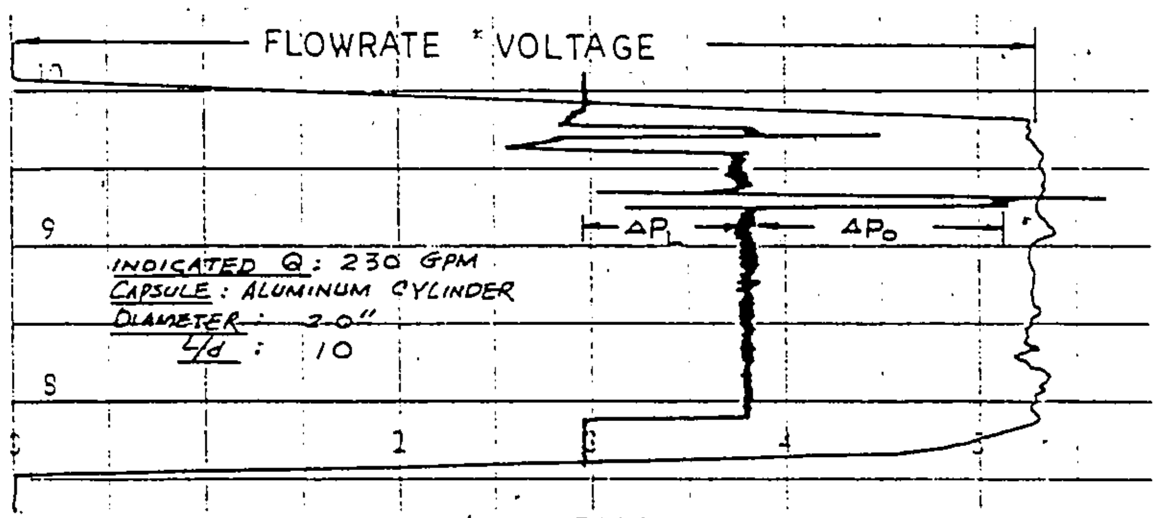
DATE 5-04-79

CAPSULE	TYPE	CYLINDER	FLOW-RATE Q (US GPM)	2" LOOP	/	DONE BY
	MATERIAL	ALUMINUM				
	DIAMETER	2.0"		3" LOOP	229.28	K. CHOW
	L/d	10				

$V_{AV} = 9.951$ fps

STAT'N	TIME (COUNTER READING) (SEC.) 1	2	3	4	5	AVG. (SEC)	V_C FT./SEC	PRESS. DROP (PSI.)	TEMP. (°C)
4-6	0.885	0.874	0.889	0.870	0.880	0.8796	4.1689	$\Delta P_L = .42$	16
6-8	0.860	0.860	0.854	0.867	0.861	0.860	4.263	$\Delta P_o = .66$	
8-10	0.858	0.866	0.864	0.842	0.847	0.854	4.293		15
10-12	0.832	0.842	0.839	0.835	0.837	0.837	4.381		
12-14	0.834	0.844	0.837	0.842	0.838	0.839	4.370	$\bar{V}_c$ = 4.375	16
14-16	0.833	0.839	0.835	0.838	0.837	0.836	4.384	(FT/SEC)	
16-19	1.231	1.276	1.274	1.261	1.260	1.260	4.363		16
								$R_V = 0.44$	
6-19	5.432	5.626	5.245	5.532	5.632	5.493	4.339		16

TABLE (5.1): SAMPLE WORK SHEET



PRESSURE & FLOWRATE DIAGRAM

station No. 10. The differences between each velocity in the section between 10 and 19 do not exceed $\pm 2\%$. Hence the average capsule velocity is

$$\overline{V}_c = (4.3808+4.3703+4.3839+4.3637)\div 4 = 4.375 \text{ ft/sec}$$
$$= 1.3335 \text{ m/s}$$

3) The Average Water Velocity:

Since the indicated flowrate is 230 GPM, Equation (5.2a) is used with the voltage V=2.65 (volts).

$$\therefore\ Q = 8+83.5\times 2.65 = 229.28 \text{ (USGPM)}$$

From Equation (5.1)

$$V_{av} = 0.01322\times 229.28 = 3.032 \quad \text{(m/s)}$$

4) The Velocity Ratio:

$$\frac{\overline{V}_c}{V_{av}} = \frac{1.335}{3.032} = 0.4398$$

5) The Pressure Gradient Due to the Fluid Alone:

Since L/d = 10 < 14 L_p = 2.79 m is used

$$\therefore\ \Delta P_L/L_p = \frac{0.42\text{(psi)} \times 6.895\text{ (KPa/psi)}}{2.79\text{ m}} = 1.0380\text{ KPa/m}$$

6) The Pressure Gradient due to the Capsule Alone:

$$L_c = 20" = 0.508 \text{ m}$$

$$\Delta P_o/L_c = \frac{0.66\times 6.895}{0.508} = 8.9581(KP_a/m)$$

7) The Pressure Gradient across the Capsule:

$$(\Delta P/L)_c = (\Delta P_o/L_c)+(\Delta P_L/L_p) = 8.9581+1.088 = 9.9961 \text{ (KPa/m)}$$

CHAPTER 6

DISCUSSION

A dimensional analysis of the system showed that for a given vertical pipeline with water, the capsule to average water velocity ratio Rv($=\frac{V_c}{V_{av}}$) and the pressure gradient ratio R_p are each a function of four independent variables: average water velocity (or Reynold's Number), diameter ratio, capsule length/diameter ratio and capsule to water density ratio.

This chapter will be mainly concerned with the discussion of the effects of these four variables on R_v and R_p on the basis of the experimental results.

6.1 <u>The Variation of Velocity Ratio R_v</u>

6.1.1 Cylindrical Capsules

Figures (6.1) and (6.2) show plots of R_v versus V_{av} respectively for nylon and aluminum cylinders. Such plots may be regarded as characteristic curves for capsule flow since they illustrate the effects of the different independent variables on the velocity ratio over the range of water velocities. However, in order to give a more clear picture of the individual effects, representative curves with R_v plotted against the individual variables are shown on separated graphs.

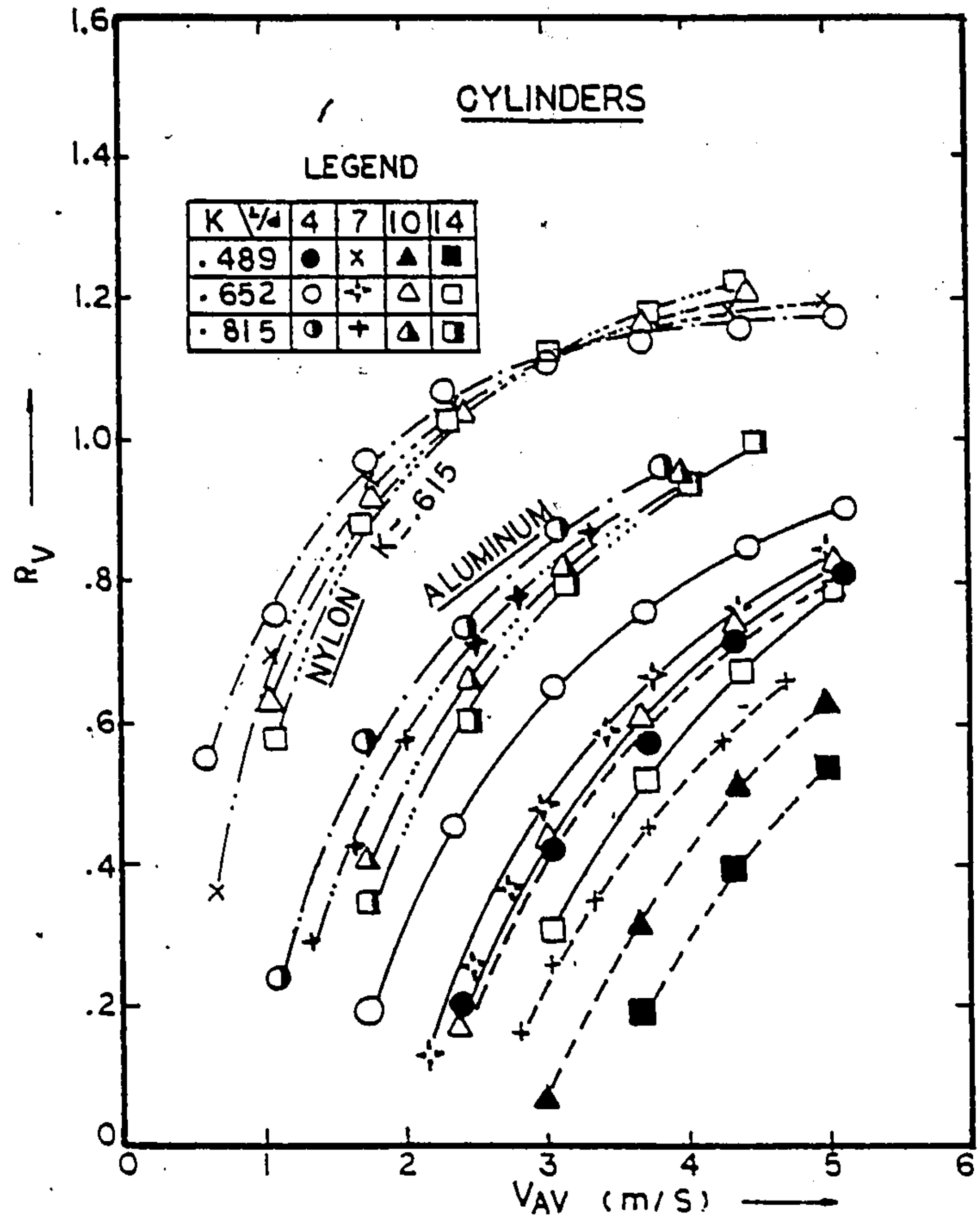


FIG. (6.1) THE VARIATION OF VELOCITY RATIO R_V WITH AVERAGE WATER VELOCITY V_{AV}

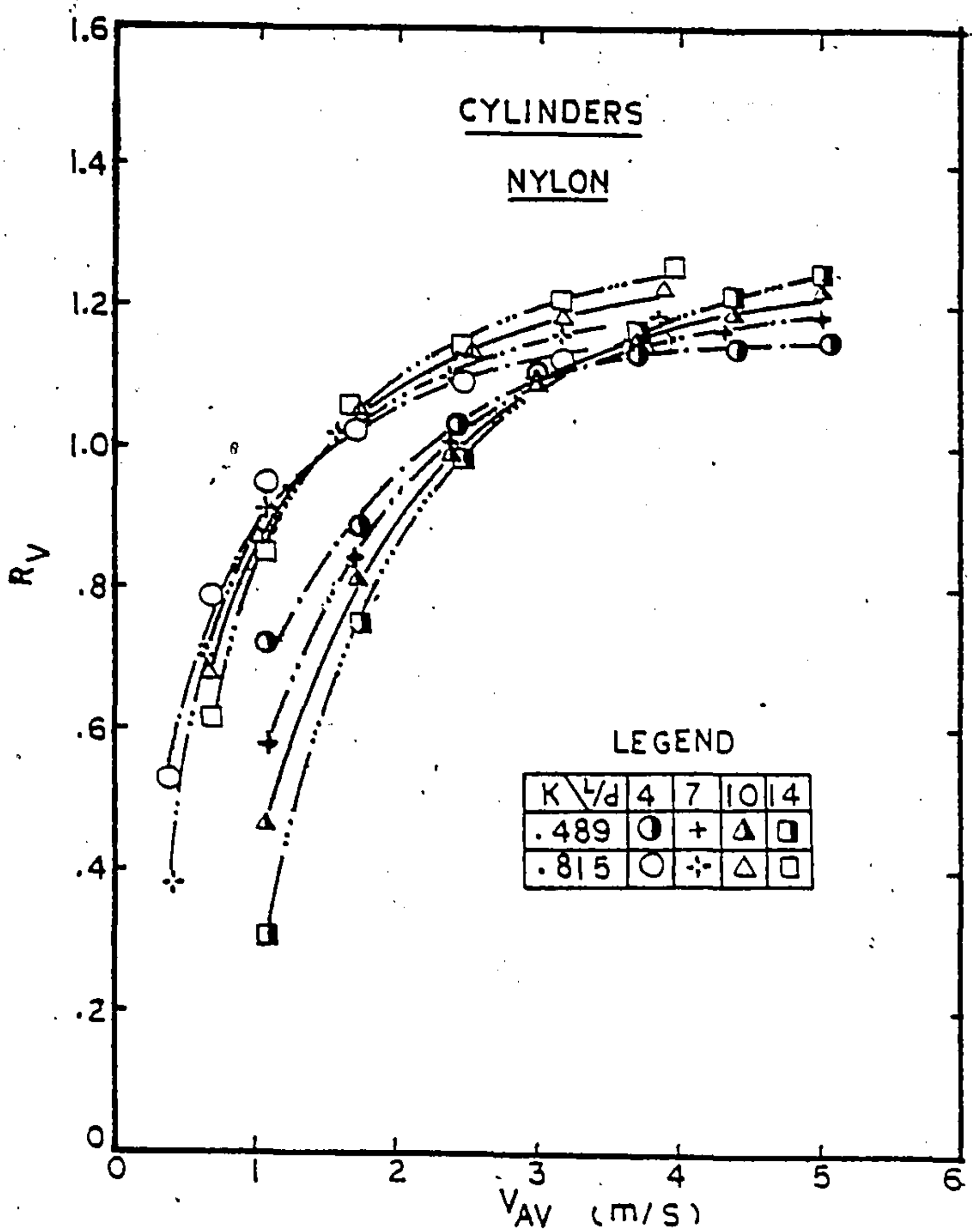


FIG. (6.2) THE VARIATION OF R_V WITH V_{AV} ; NYLON CYLINDERS OF K = .489 & .815

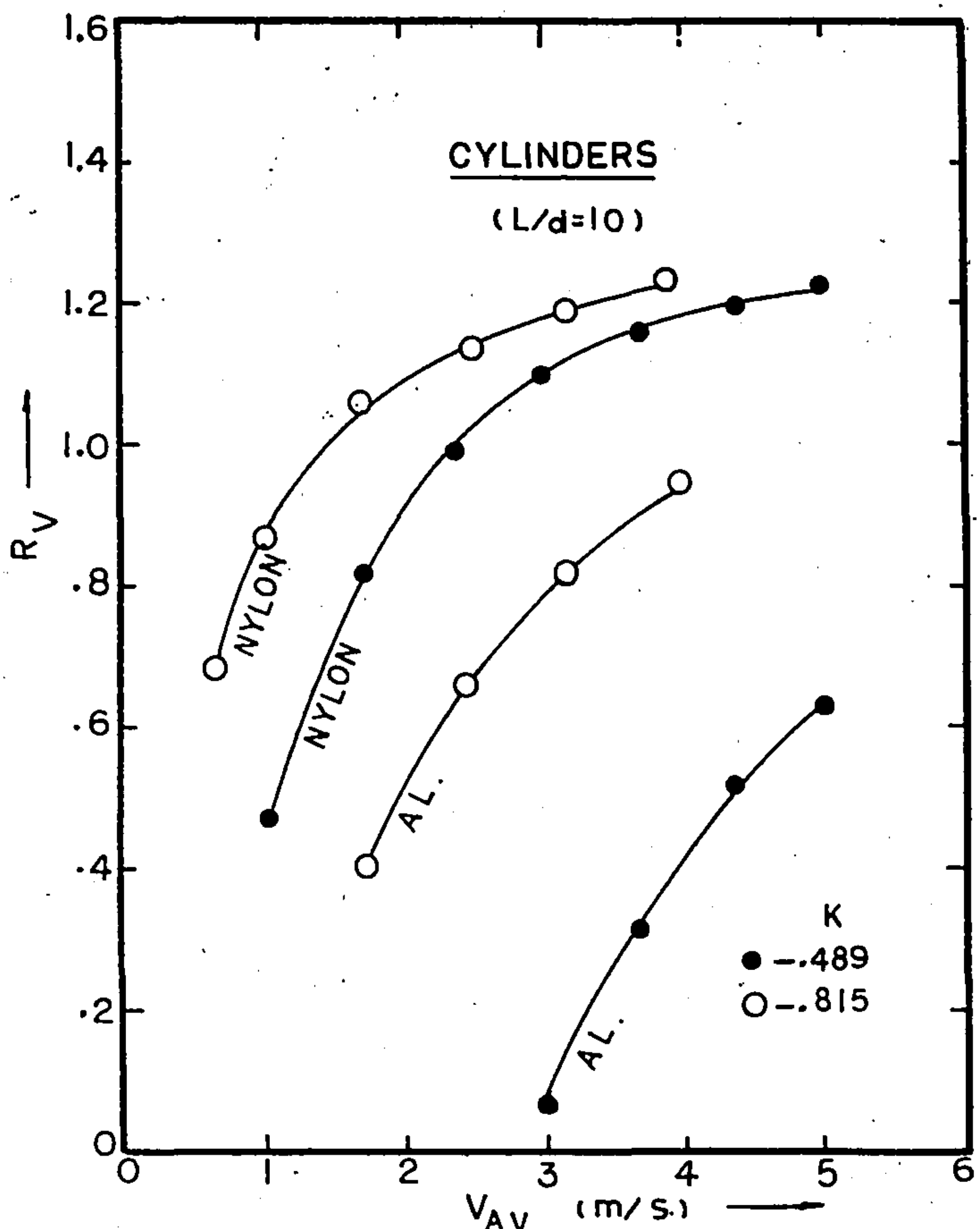


FIG.(6.3): THE EFFECT OF V_{AV} ON R_V; NYLON AND ALUMINUM CYLINDERS OF L/d=10

6.1.1.1 The Effect of V_{av} on R_v

Figure (6.3) shows the representative curves of R_v versus V_{av} for the largest and the smaller capsules of the same L/d ratio. From Figures (6.1) to (6.3) the following observations were obtained:

(i) The characteristic curves are qualitively of the same general shape for both nylon and aluminum cylinders. This implies that a general correlation between R_v or V_c and the other independent variables may exist.

(ii) Each of the curves when extrapolated intersects the V_{av} axis. The intersection represents the minimum average water velocity needed to suspend the particular capsule. The value of the suspension velocity is directly proportional to the capsule's length and density but is inversely proportional to the diameter of the capsule.

(iii) Once the capsule begins to move, R_v increases with increase of V_{av}. This is a result of the increase of the pressure forces on the capsule, (Cf. Equation (3.5)). It must be born in mind that the velocity ratio is based on the average capsule velocity and water velocity. Hence the curve of R_v versus V_{av} for a given capsule represents the equilibrium state at each water velocity. At the equilibrium state the total thrust force, which is equal to the buoyed weight of the capsule, is the sum of the pressure and shear forces. The pressure force will increase with increase of

V_{av}, so that the thrust due to the shear force will have to decrease. This latter result can only be brought about by a decrease of the average water velocity in the annular space since the shear force is dependent on it. From Equation (3.4), which can be rewritten as:

$$R_V = V_C/V_{av} = 1 - \frac{(V_N-V_C)}{V_{av}}(1-K^2) \qquad (6.1)$$

It is seen that a decrease of (V_N-V_C) with an increase of V_{av} will lead to an increase of R_V, for a given capsule.

(vi) Over the entire range of V_{av} employed, R_V for the nylon cylinders reach maximum values ranging from 1.15 to 1.25, while those for alumimum cylinders never reached a value greater than unity. This is due to the effect of the density of the capsule and will be dealt in detail in the discussion of density effects.

For nylon cylinders the R_V ratio tends to become constant after they have attained $R_V > 1.0$. The reason appears to be that under this condition a capsule behaves as though it had neutral buoyancy. A neutral buoyancy capsule would be carried along the pipeline at the same velocity as that of the carrier fluid which immediately follows it. In other words the velocity of the capsule is dependent on its position with respect to the flow velocity profile or the region of the pipe cross section it occupies. Hence the maximum velocity which a capsule

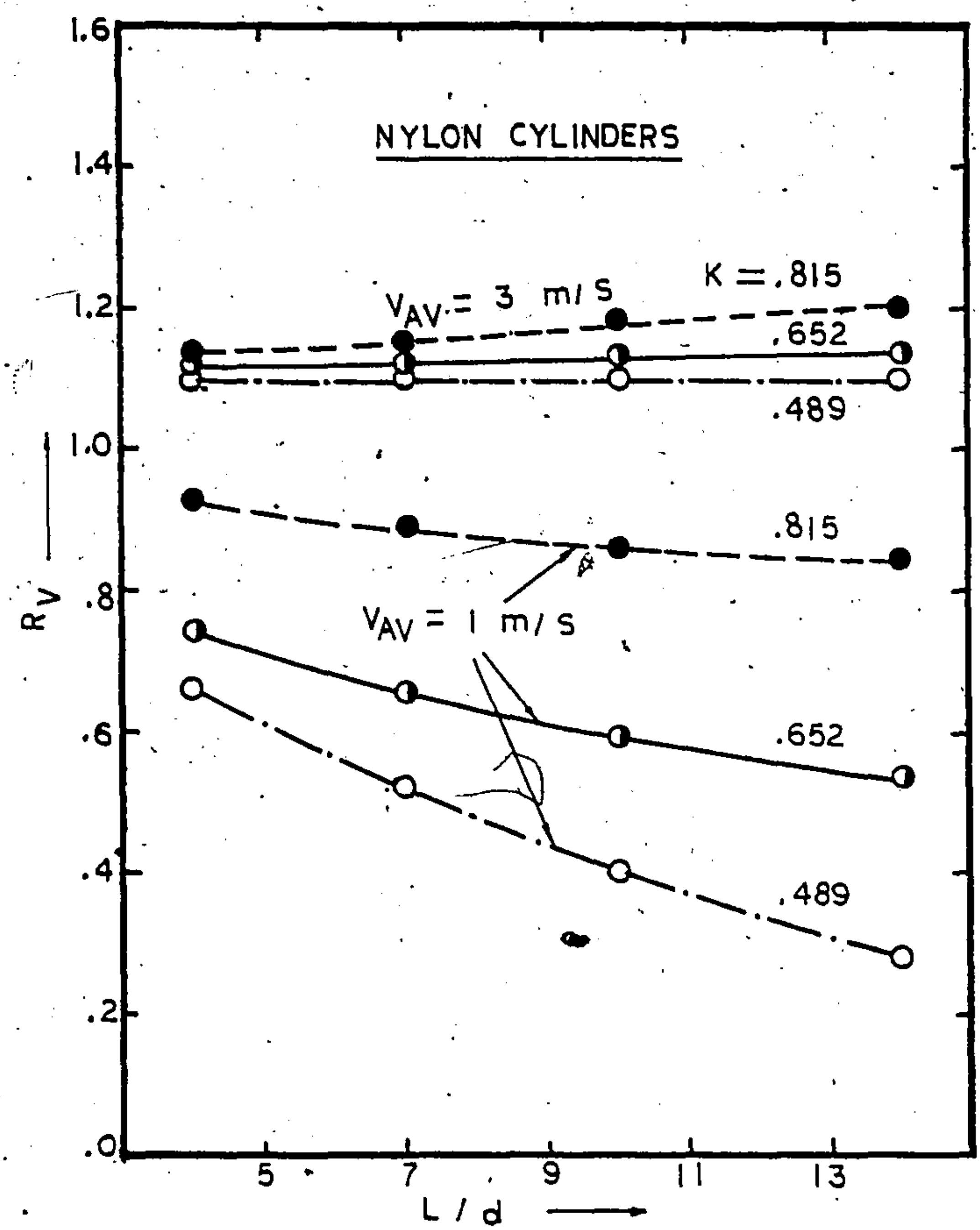


FIG.(6,4). THE EFFECT OF L/d ON R_V : NYLON CYLIDERS

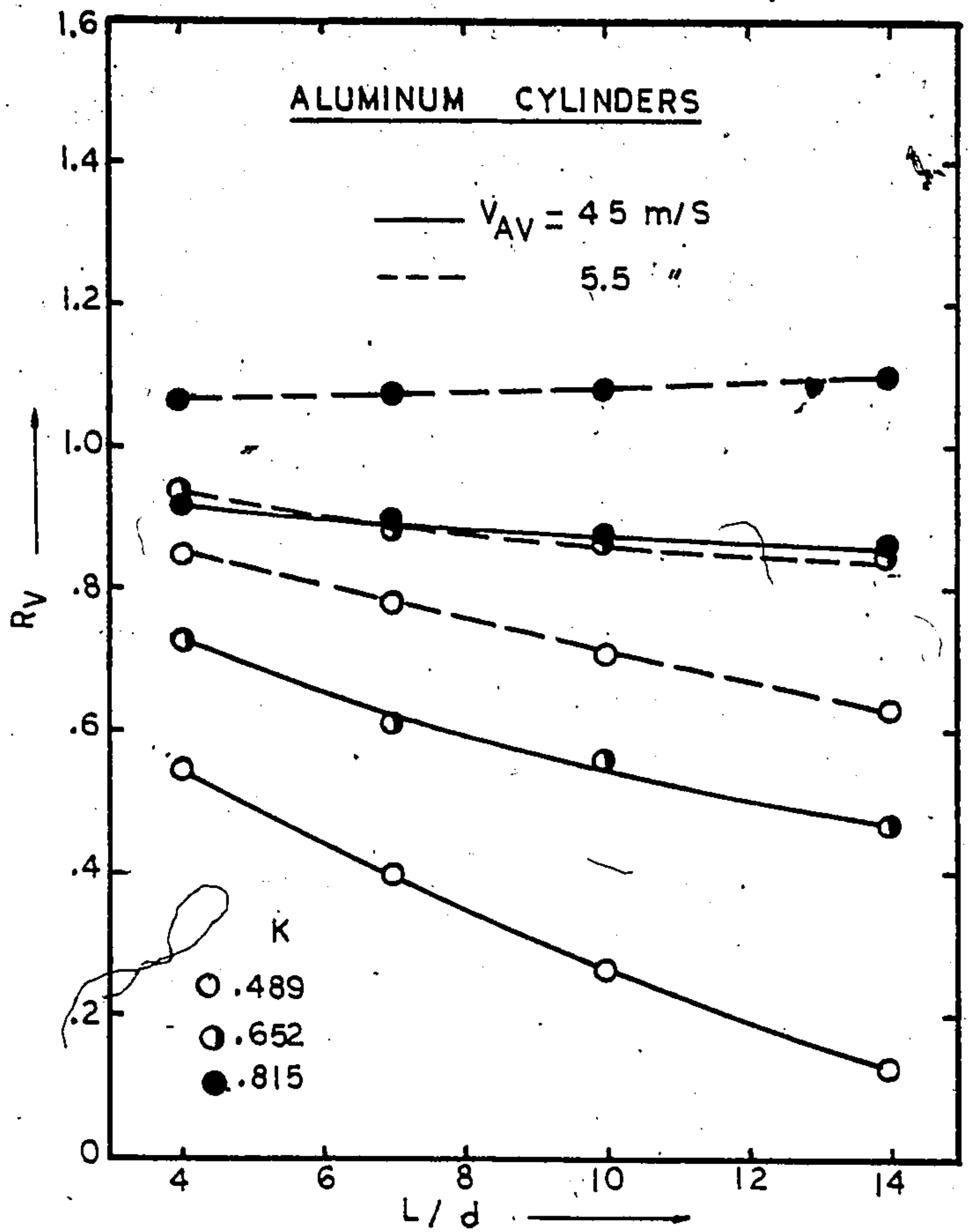


FIG. (6.5) THE EFFECT OF L/d ON R_V ... ALUMINUM CYLINDERS could possibly attain is the average value of the part of the profile at which the capsule is situated. Hence, if the capsule reaches the maximum velocity, the velocity ratio is invariant with V_{av} but dependent on K only.

6.1.1.2 <u>The Effect of L/d on</u> R_v

Figures (6.4) and (6.5) are the representative plots of R_v versus L/d respectively for nylon and alumimum cylinders for three K at two different V_{av}'s. Data for these curves were derived from Figures (6.1) and (6.2).

Both Figures (6.4) and (6.5) show that, when $R_v < 1.0$, for the same material and K, the longer capsules move slower than the shorter ones at a constant V_{av}. However this condition is reversed when $R_v > 1.0$. This phenomenon is also clearly shown in Figures (6.1) and (6.2), in which the curves for the longer capsules of the same K always lie below that for the shorter ones when $R_v < 1.0$, but is reversed and lie above when $R_v > 1.0$.

The reason for the different effects of L/d ratio on R_v at low and high V_{av} is thought to be due to the fact that eddies formed at the ends of the capsule change ends thereby changing the direction of the force arising from the eddies on the capsule. Normally eddies are formed after the trailing end of a body. However for bounded media, such as capsule-pipeline flow, this phenomenon can be reversed since the fluid in the annular space may be at a velocity greater than the body, thus producing a situation where the eddies are created at the leading face of the body. Similar situation can be happening at a capsule since the direction of the annular fluid velocity relative to the capsule (V_N-V_C), or the relative velocity of V_{av} with respect to V_c, $(V_{av}-V_c)$, can be reversed. Hence if $V_c < V_{av}$ the eddies are formed on the nose, however, if $V_c > V_{av}$ they are formed at the tail. Thus the force arising from the eddies exerts a thrust force on the capsule if $V_c < V_{av}$ and a drag force if $V_c > V_{av}$. In both cases the shorter, and therefore the lighter of the capsules that were used,were more affected by this force since for a given K and V_{av} this force is constant regardless of the capsule length. Therefore at low V_{av} the shorter capsules move faster and at high V_{av} move slower than the longer ones.

The effect of increasing L/d ratio on R_v when $R_v < 1.0$ is more pronounced as V_c is decreased. This is shown in Figures (6.1) and (6.2), in which the curves for the capsules of constant K tend to be more divergent as the suspension velocity is approached. This may be explained by the fact that the eddies effect on the capsule is at its greatest at the suspension velocity because $(V_{av}-V_c)$ is then at its greatest value, causing the largest difference in R_v between the different lengths of capsules. As the capsule starts to move the value of $(V_{av}-V_c)$ decreases and so does the effect of the eddies, hence causing a smaller difference in R_v. This indicates a decrease in the importance of variation of the length of a long capsule of constant K as the length is increased especially when $K \geq 0.65$. This point is significant in regard to the use of long trains of capsule.

(iii) The Effect of K on R_v

Figures (6.6) and (6.7) give plots of R_v versus K for both nylon and aluminum cylinders for all L/d ratios investigated at various V_{av}.

At constant L/d and V_{av}, R_v increases with increase of K at all water velocities. The reason, which also explains the variation of suspension velocity with diameter, is that the increase of base pressure force due to the increase of base area of the capsule is larger than the corresponding increase of weight. The effect of the diameter ratio can be explained by referring Equation (3.5) which can be written, in terms of the total pressure drop ΔP across the capsule and the wall shear stress τ_c on the capsule, as

$$\Delta P \frac{\pi d^2}{4} \pm \pi d L \tau_c = (\sigma - \rho) g \frac{\pi d^2}{4} L$$

$$\text{or } \left[\frac{\Delta P}{(L/d)K}\right] \pm \frac{4\tau_c}{K} = (\sigma - \rho) g D \qquad (6.2)$$

In which $(\sigma-\rho)gD$ is constant for a capsule of given material in a given diameter of pipe. However the pressure drop is not constant for different capsules of different

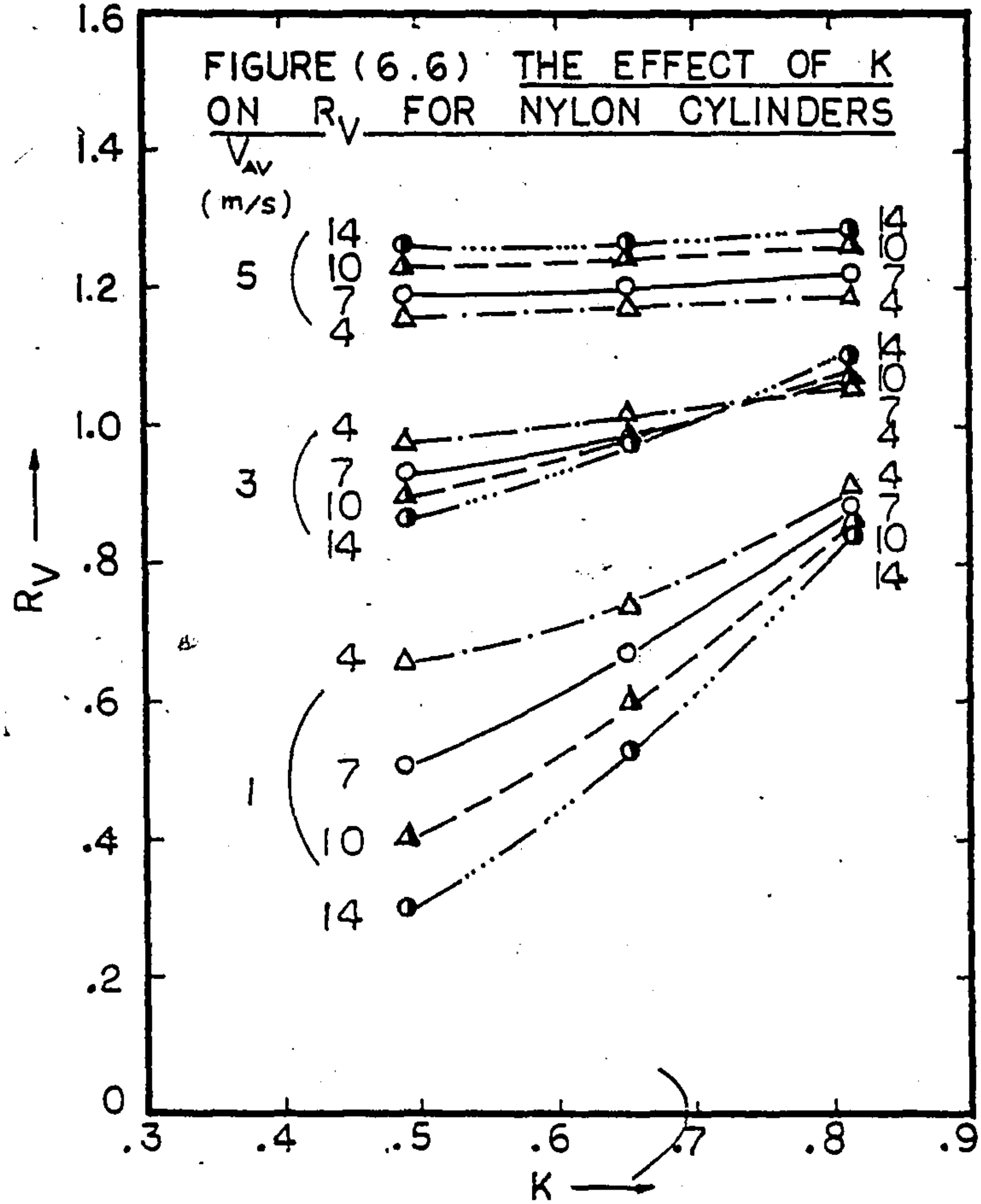


FIGURE (6.6) THE EFFECT OF K ON R_V FOR NYLON CYLINDERS
V_{AV} (m/s)
5
3
1
14
10
7
4
R_V
K
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
.3
.4
.5
.6
.7
.8
.9

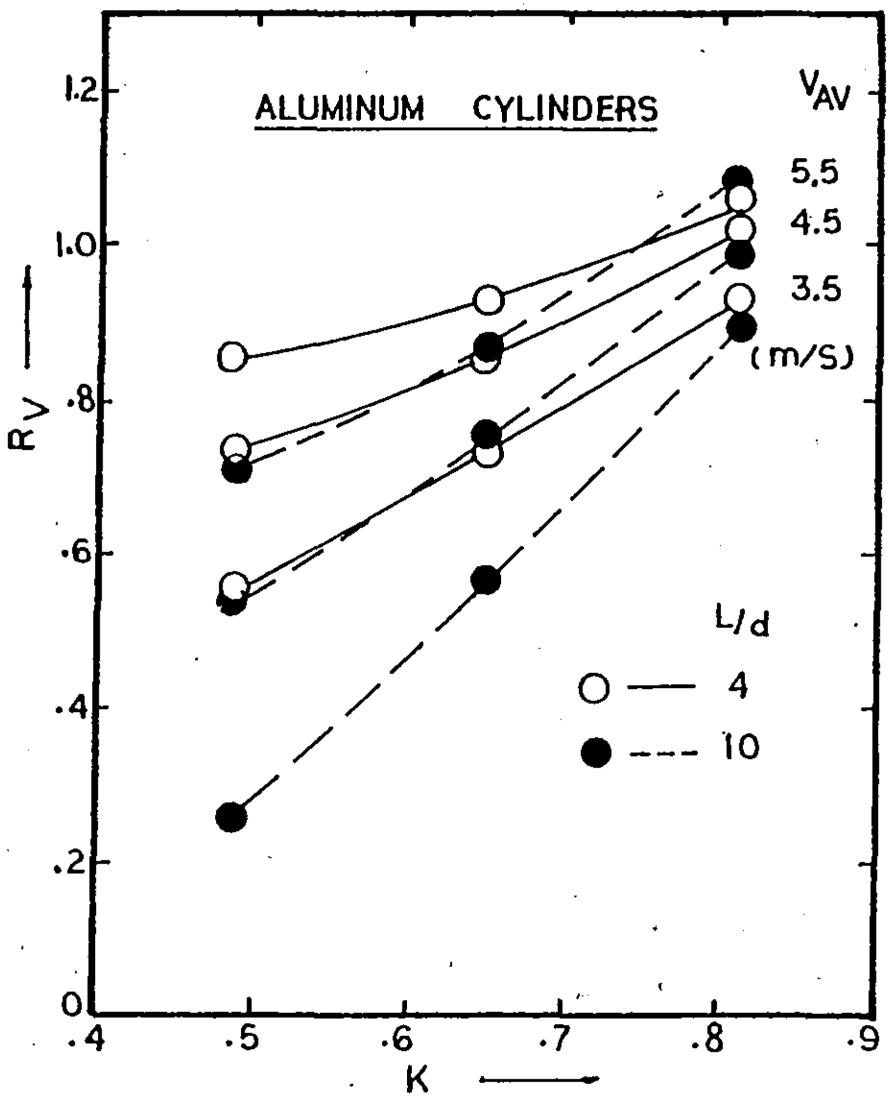


FIG. (6.7) THE EFFECT OF K ON R_V FOR ALUMINUM CYLINDERS

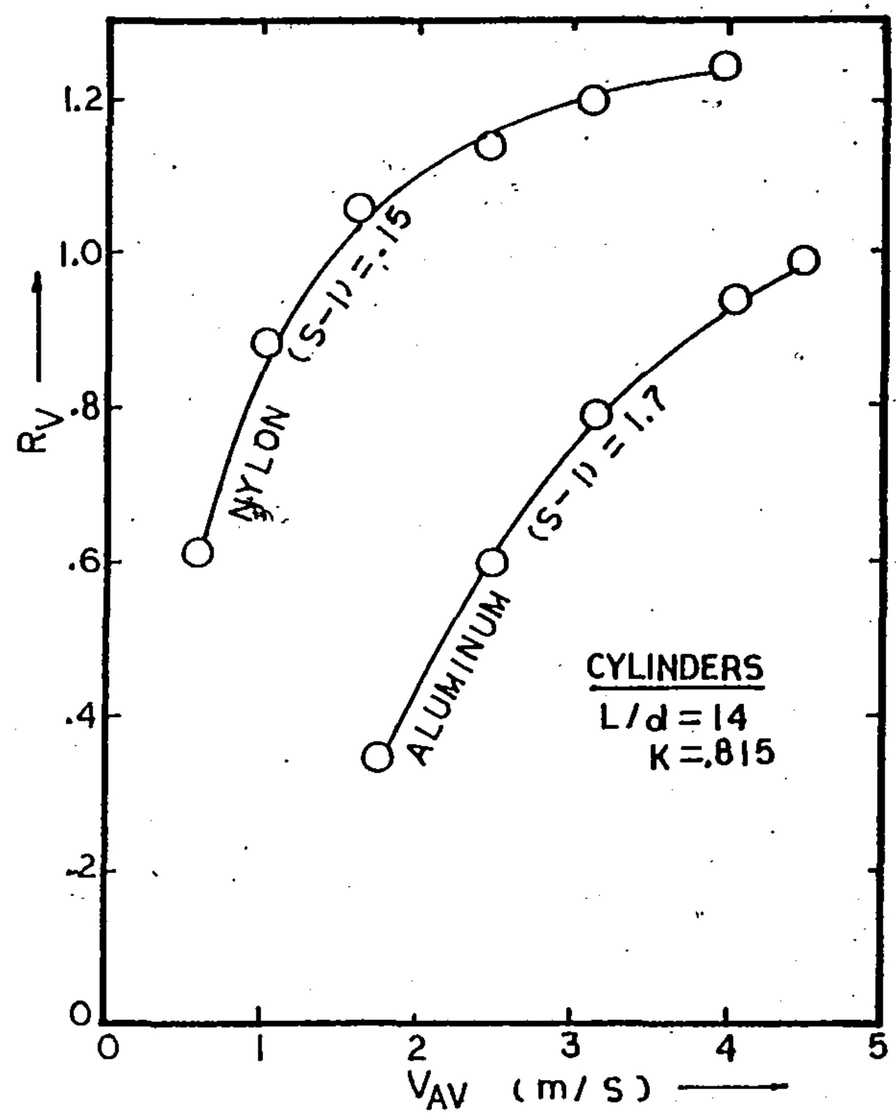


FIG. (6.8) THE EFFECT OF DENSITY RATIO ON R_V FOR CYLINDERS diameter at a constant V_{av}. In fact it increases with an increase of K and in such a way that it always produces a net increase in the pressure drag, so that the first term of Equation (6.2) always increases with increase of K. The τ_c/K term also changes with K. The change due to K, however, is insufficient to compensate for the increase of the pressure term, because the shear force is usually much smaller than the pressure force for a capsule with K approaching 1.0. Hence τ_c may decrease or increase to satisfy Equation (6.2). Since V_{av} is kept constant, the decrease or increase of τ_c can only be brought about by an increase or decrease in V_c. Therefore with an increase of K, V_c has to increase for $R_v < 1.0$ and decrease for $R_v > 1.0$. Although the latter effect in the region of $R_v > 1.0$ is not obvious in the figures, the curves for smaller capsules do have a tendency to cross those of the larger ones at high V_{av}.

The effect of varying K on nylon cylinders at constant L/d and V_{av} is much less than that on aluminum cylinders. This is evidently due to the lower density ratio of the nylon cylinders.

(iv) <u>The effect of</u> $(\frac{\sigma-\rho}{\rho})$ on R_v.

The effect of increasing σ, other parameters being constant, is to decrease R_v, but the effect gradually decreases as V_{av} increases. Figure (6.8) shows data for nylon and aluminum cylinders of K = 0.815 and L/d = 14 for various V_{av}'s. At low V_{av}, e.g. $\leq$ 2 m/s, R_v for the nylon cylinder is 2.44 times that for the aluminum cylinders, but at a higher V_{av}, e.g. V_{av} = 4 m/s, R_v for nylon cylinder is only 1.33 times greater than that for the aluminum one. The reason for decreasing R_v by increasing σ is obvious since an increase in σ, other parameters being constant, means an increase in weight of the capsule, and a heavier capsule requires a higher suspension velocity than the lighter ones do. In a latter section (6.2.1) we will introduce a new velocity term, $(V_{av}-V_o)$, which is the net increase of water velocity above the suspension velocity. It is found that R_v is directly proportional to $(V_{av}-V_o)$. Hence a heavier capsule will be subjected to a smaller value of $(V_{av}-V_o)$ than the lighter ones will, and hence having a lower R_v at a fixed V_{av}.

The phenomenon of decreasing effect of σ on R_v with an increase of V_{av} indicates that the importance of σ becomes less at high V_{av}. This point is significant in regard to the transport of high density of capsules.

6.1.2 Spherical Capsules

A dimensional analysis showed that the velocity ratio, R_v, of a single sphere being carried by water in a given pipeline is a function of three independent variables: V_{av}, K, and $(\frac{\sigma-\rho}{\rho})$. The effect of the individual variables as

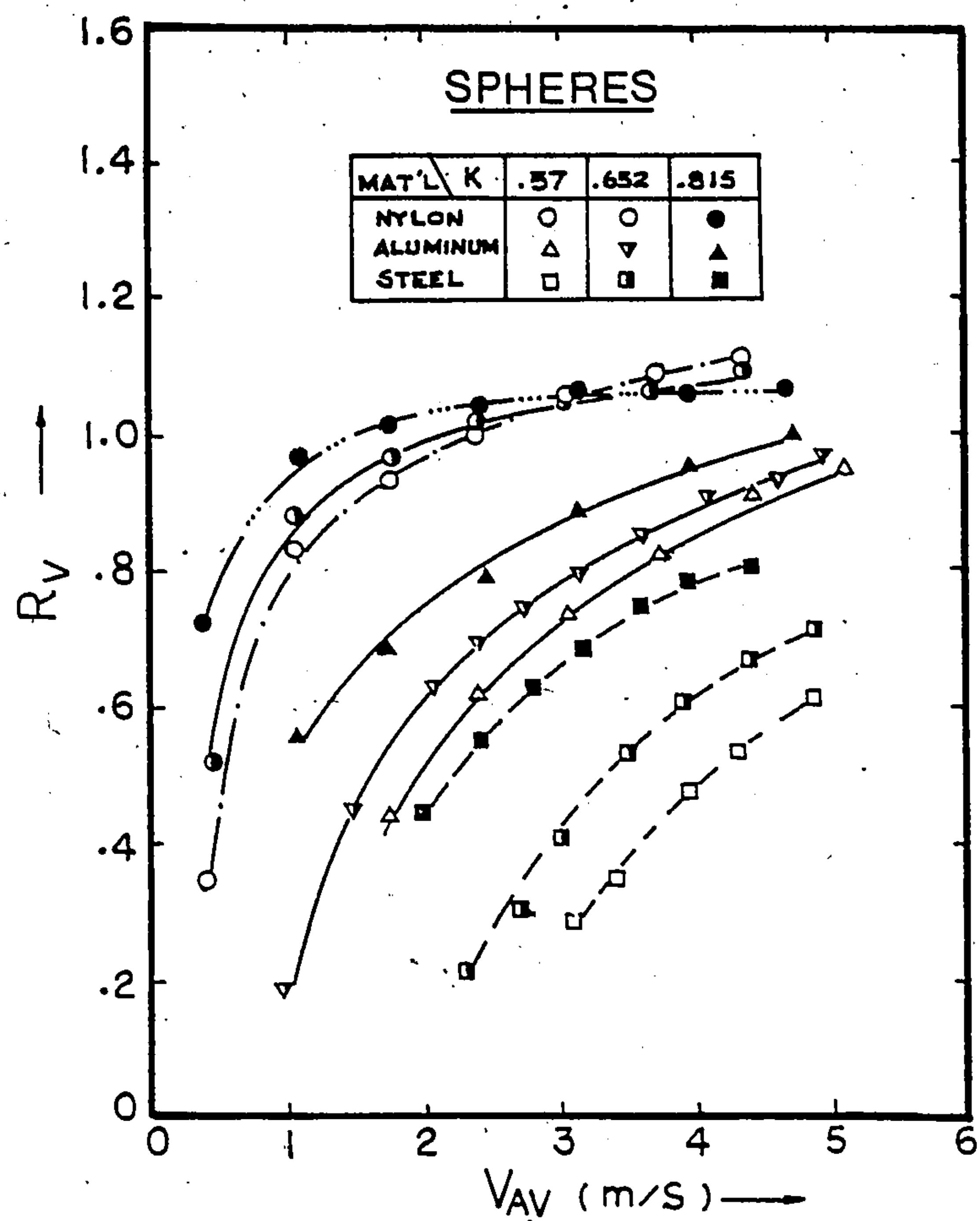


FIG. (6.9) : THE VARIATION OF R_V WITH V_{AV} : SPHERICAL CAPSULES indicated in the experiment will now be discussed.

6.1.2.1 The effect of V_{av} on R_v

Figure (6.9) shows a plot of R_v versus V_{av} for single spheres of three different materials and diameter ratios. As was observed for cylindrical capsules, the curves may be considered as characteristic plots for capsule flow of single spheres.

In general R_v for any diameter spheres increases with an increase of V_{av}, the same trend as that of cylindrical capsules. It has been previously stated in connection with the cylindrical capsules that the increase of V_{av} causes the pressure force to increase in Equation (3.5), resulting in an increase of capsule velocity. The same reasoning is followed for spherical capsules because Equation (3.5) holds for any regular shape capsules in a vertical pipeline.

As was the case for cylindrical capsules, only the curves for nylon spheres reach R_v greater than unity. Aluminum and steel spheres had never reached $R_v > 1.0$ for the range of V_{av}'s.

At a V_{av} of about 2.5 m/s, $V_c > V_{av}$ for all the nylon spheres. With V_{av} greater than that, the largest diameter ratio (e.g. 0.815) nylon sphere attains a constant R_v of 1.02, but for other diameter ratios (0.652 and 0.57) R_v still increases and becomes larger than that for K = 0.815 when $V_{av} \simeq 3$ m/s. The phenomenon, that the larger capsules would eventually be overtaken by the smaller ones at high V_{av}'s, has been pointed out for the case of cylindrical capsules to be the result of increasing the diameter ratio in accordance with Equation (3.5). The reason that this phenomenon was not observed for cylindrical capsules but was so for spheres is thought to be the consequence of the difference in the capsule end configurations. The spherical capsules have more streamlined noses than cylindrical capsules and the effects of the nose geometry are more pronounced on the R_v ratio as K approaches zero. Therefore it may be expected that the tendency for small capsules to overtake large ones would be more pronounced for spherical than cylindrical capsules. Studies of the effects of capsule and configurations have been made by Ellies (6), Round et al (10) and Lee (23). They reported that the effects of modifying the noses of capsules on R_v increased as diameter ratio K approached to zero.

Comparison of the curves for nylon capsules in Figures (6.1) through (6.9) shows that the spherical capsules have a higher R_v than that for cylinders for low V_{av} (i.e. $R_v < 1.0$) but is the reverse for high V_{av} ($R_v > 1.0$). For instance, the nylon sphere of $K = 0.652$ and the nylon cylinder of the same K at $L/d = 4$ have R_v's of 0.86 and 0.75 respectively when $V_{av} = 1$ m/s, and R_v's of 1.06 and 1.16 when $V_{av} = 4$ m/s. This difference is evidently due to the length or viscous effects of the capsule, since the spheres have in effect an

$L/d = 1.0$ and are therefore the shortest capsules that were studied. It has been pointed out in connection with the cylindrical capsules that a shorter capsule moves faster at low V_{av}'s but is slower at high V_{av}'s than the longer capsule of the same K and material at a given V_{av}. The same reasoning explains why the aluminum spheres always move faster than the aluminum cylinders for the same V_{av}.

6.1.2.2 <u>The effect of K on</u> R_v

Figure (6.10) shows a plot of R_v versus K for nylon, aluminum and steel spheres having K's of 0.57, 0.652 and 0.815 at various V_{av}.

In general the effect of increasing K is to increase R_v at a decreasing rate for constant V_{av}. This is evidenced by the decreasing slope of each curve as V_{av} increases in the region of $R_v < 1.0$ on Figure (6.10). However, in the region of $R_v > 1.0$, an increase of K has a reverse effect on the R_v ratio. The latter phenomenon suggests the possibility of using a more streamlined nose to increase the R_v ratio for smaller diameter capsules at high V_{av}'s.

During the experiments with spheres, noise was created by the sphere violently knocking against the pipe wall as it progressed up the test section. Unfortunately, it was not possible to observe the motion of the spheres. However, it is believed that the sphere was travelling in a spiral eccentric path and colliding with the pipe wall. As V_{av} and

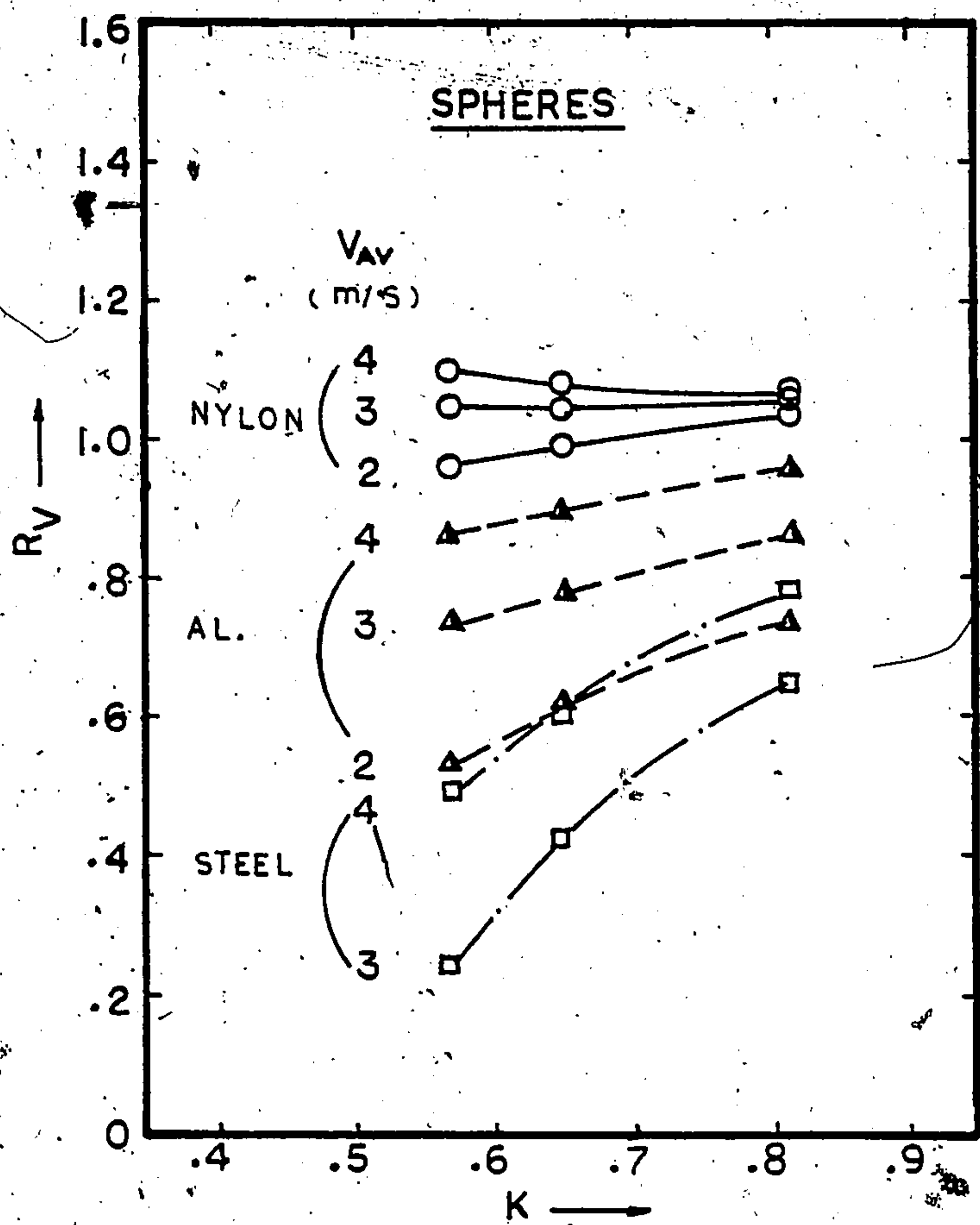


FIG. (6.10): THE EFFECT OF K ON R_V : SPHERES OF NYLON, AL. & STEEL

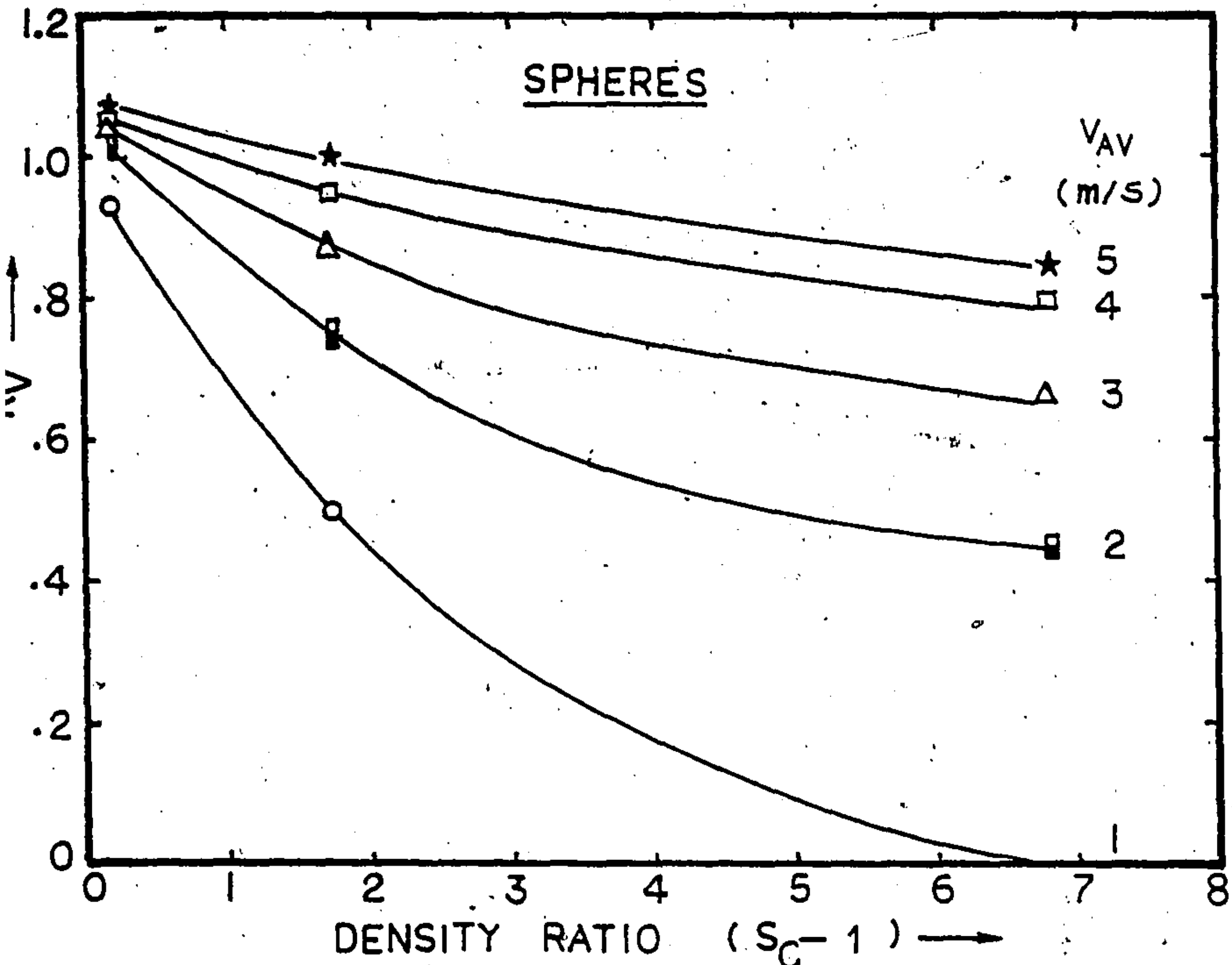


FIG. (6.11): THE EFFECT OF DENSITY RATIO ON R_V: SPHERES OF K = .815

K were increased the noise level increased. This meant that the frequency of contact between the capsule and the pipe wall increased, which resulted in an increase of drag force on the sphere due to the erratic motion and impacts. As a result the rate of increase in R_V for the larger spheres decreases with increase of V_{av}. This might be considered as one of the reasons why the larger spheres moved slower than the smaller ones at high V_{av}'s.

6.1.2.3 The effect of $(\frac{\sigma-\rho}{\rho})$ on R_V

Figure 6.11 is a plot of R_V against the density ratio $(\frac{\sigma-\rho}{\rho})$ for nylon, aluminum and steel spheres of the same K (i.e. 0.815) at various V_{av}'s. The effects of increasing the density ratio at any particular V_{av}, as for the case of cylindrical capsules, is to decrease R_V. The density effect is much more pronounced at low than at high V_{av}'s, the same trend as seen in the case of cylinders.

6.2 Correlations for the Prediction of V_c

One important part of the study was to find the correlations between V_c and the pertinent parameters so that the value of V_c can be predicted for a given capsule-pipeline system. Much effort was put into this aspect and empirical correlations based on the experimental data were established. The correlations for both cylindrical and spherical capsules are presented as follows:

6.2.1 Cylinders

Graphs of V_c versus V_{av} are presented on Figures 6.12 to 6.16. The curves for each capsule is a straight line and the intersection of which with the V_{av} axis gives the suspension velocity V_o for the capsule. However, the most useful graphs in correlating V_c to V_{av} are those with V_c plotting against the net increase of water velocity above the suspension velocity, $(V_{av}-V_o)$, as shown in Figures 6.17 to 6.19. These graphs show that: (1) The curves, for most of the range of V_{av} investigated, are straight lines passing through the origin; (2) Most of the data points of nylon and aluminum cylinders of the same K and L/d ratio fall on the same line. This indicates that the slope of the line is independent of capsule density; (3) The slopes of the straight lines increase with an increase of L/d and decrease with increasing K ratio. An equation for the straight lines with the slope, m, is hence obtained as:

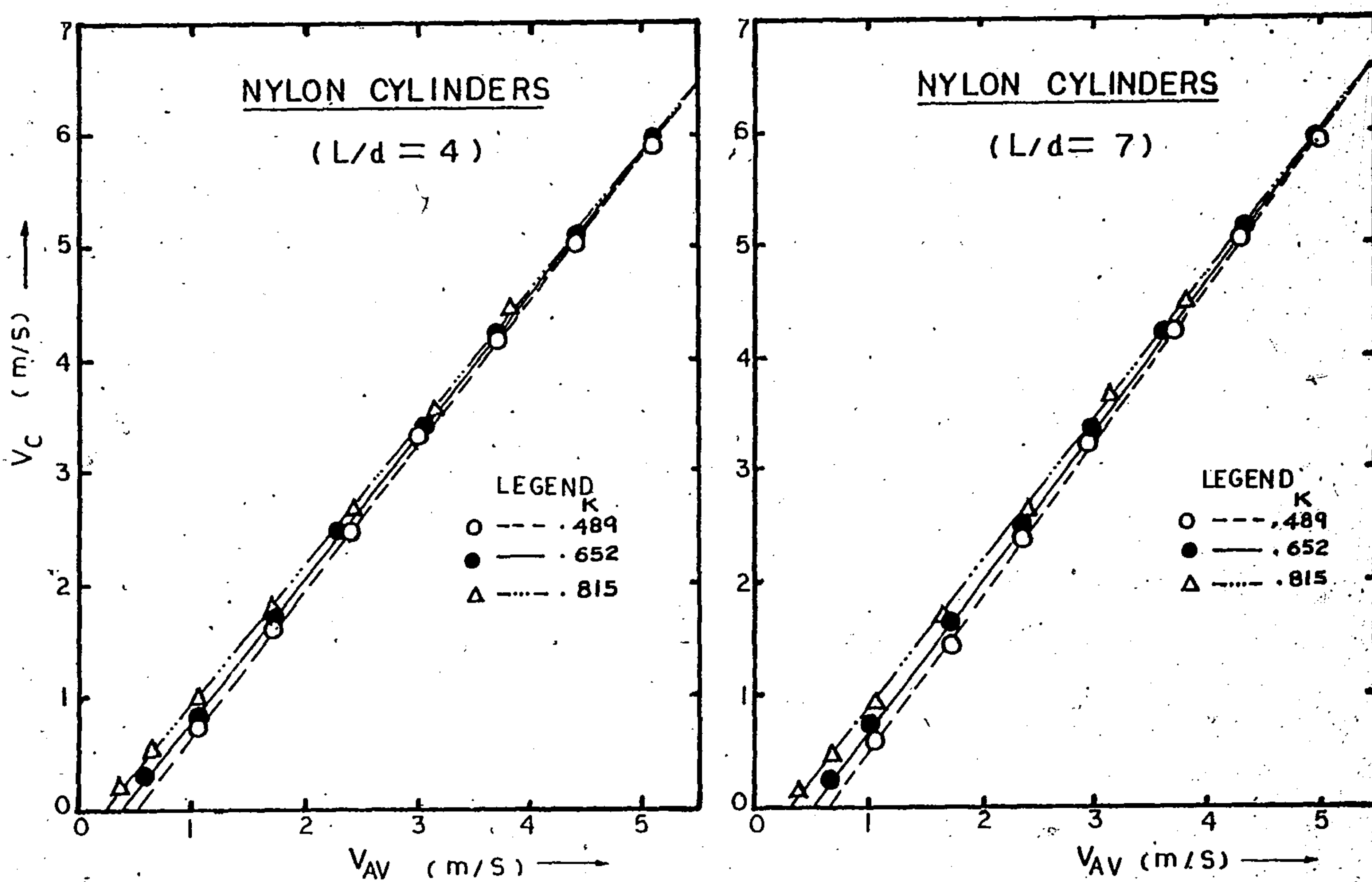
$$V_c = m(V_{av}-V_o) \qquad 6.3a$$

where $m \propto (L/d)/(K)$

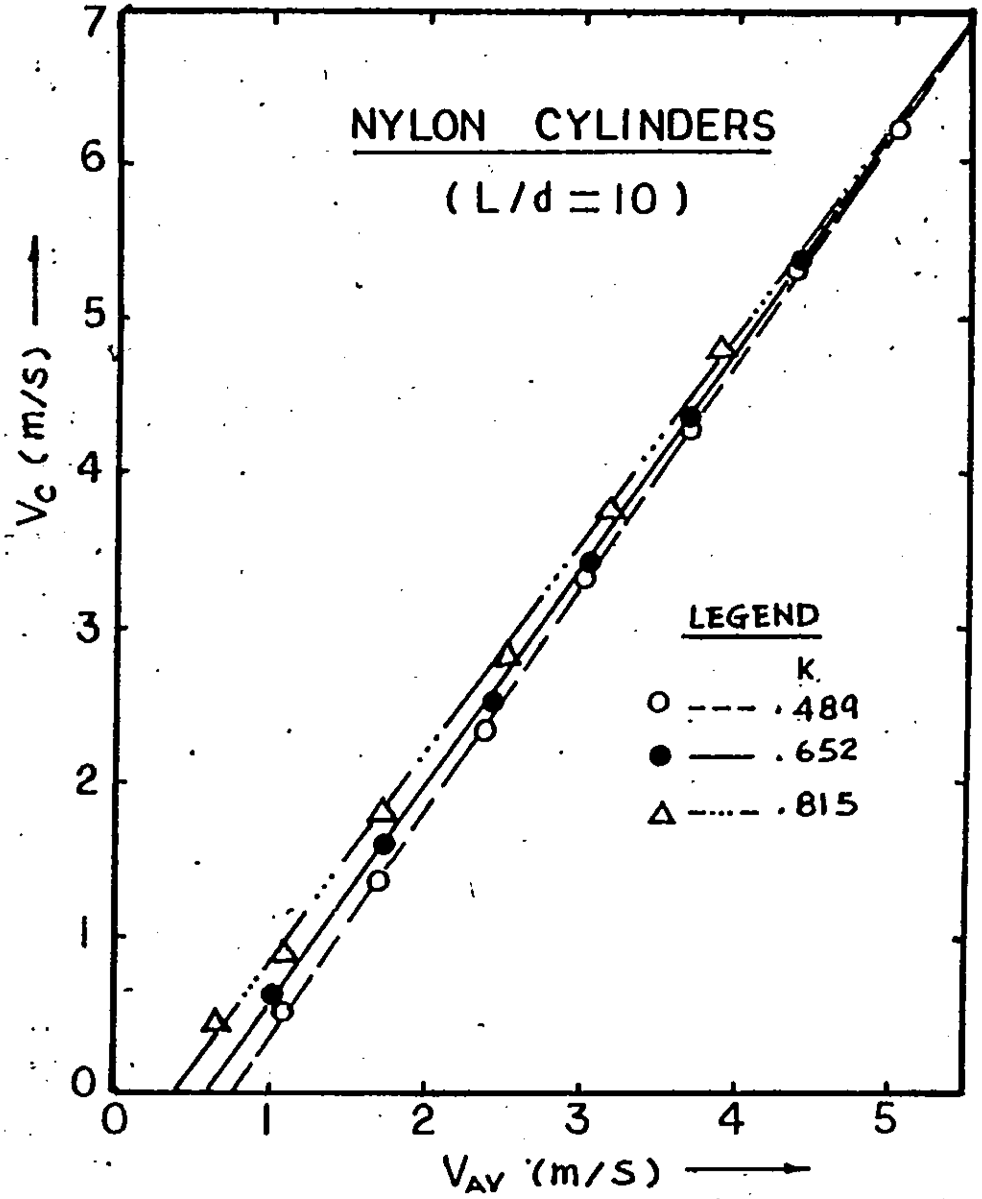
$$\text{or} \quad m = (L/d)^A/(K)^B \qquad 6.3b$$

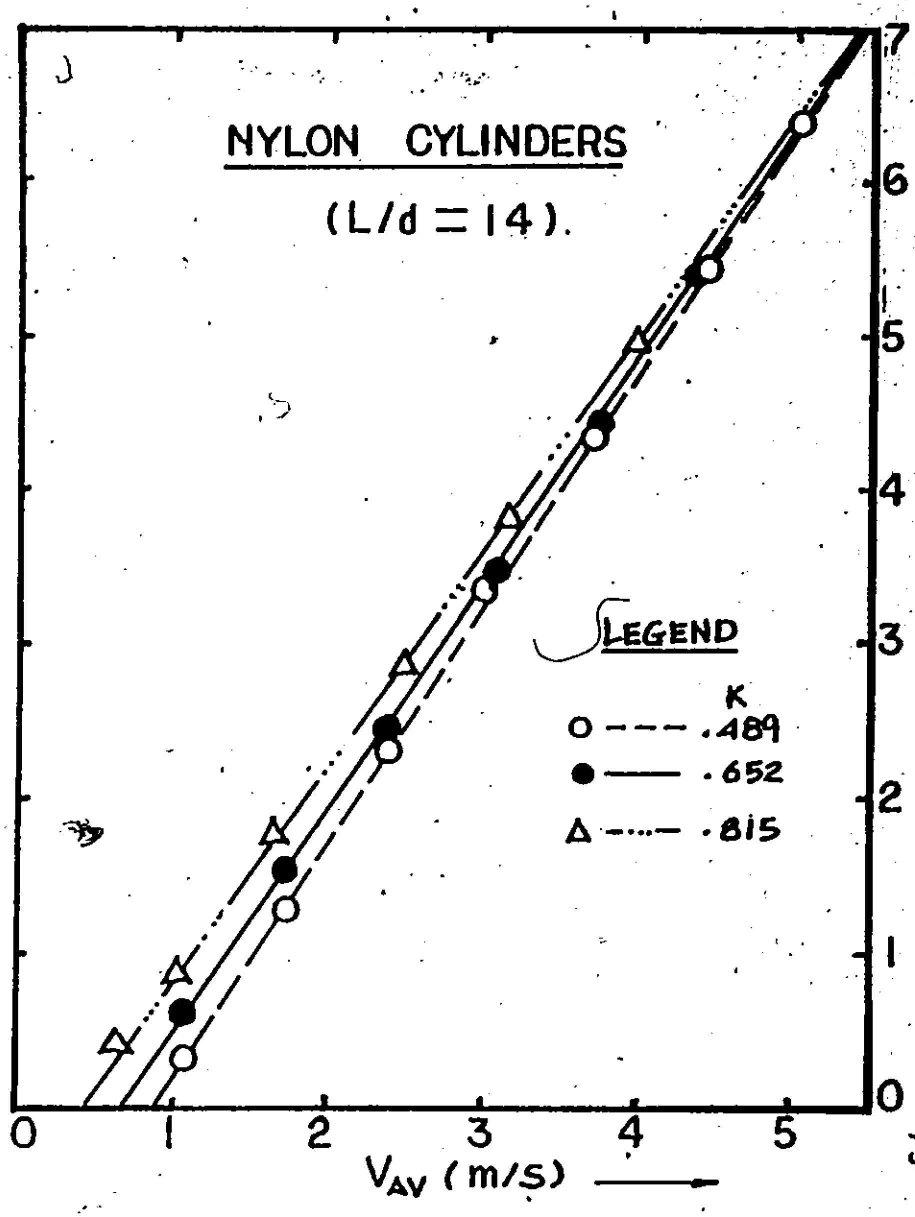
By means of log-log plotting both constant A and B were found to have a value of 0.128. Therefore Equation (6.3a) becomes

$$V_c = \frac{(L/d)^{0.128}}{(K)^{0.128}}(V_{av}-V_o) \qquad 6.3c$$



FIGURES (6.12, 13): V_C VERSUS V_{AV}





FIGURES (6.14, 15) V_C VERSUS V_{AV}

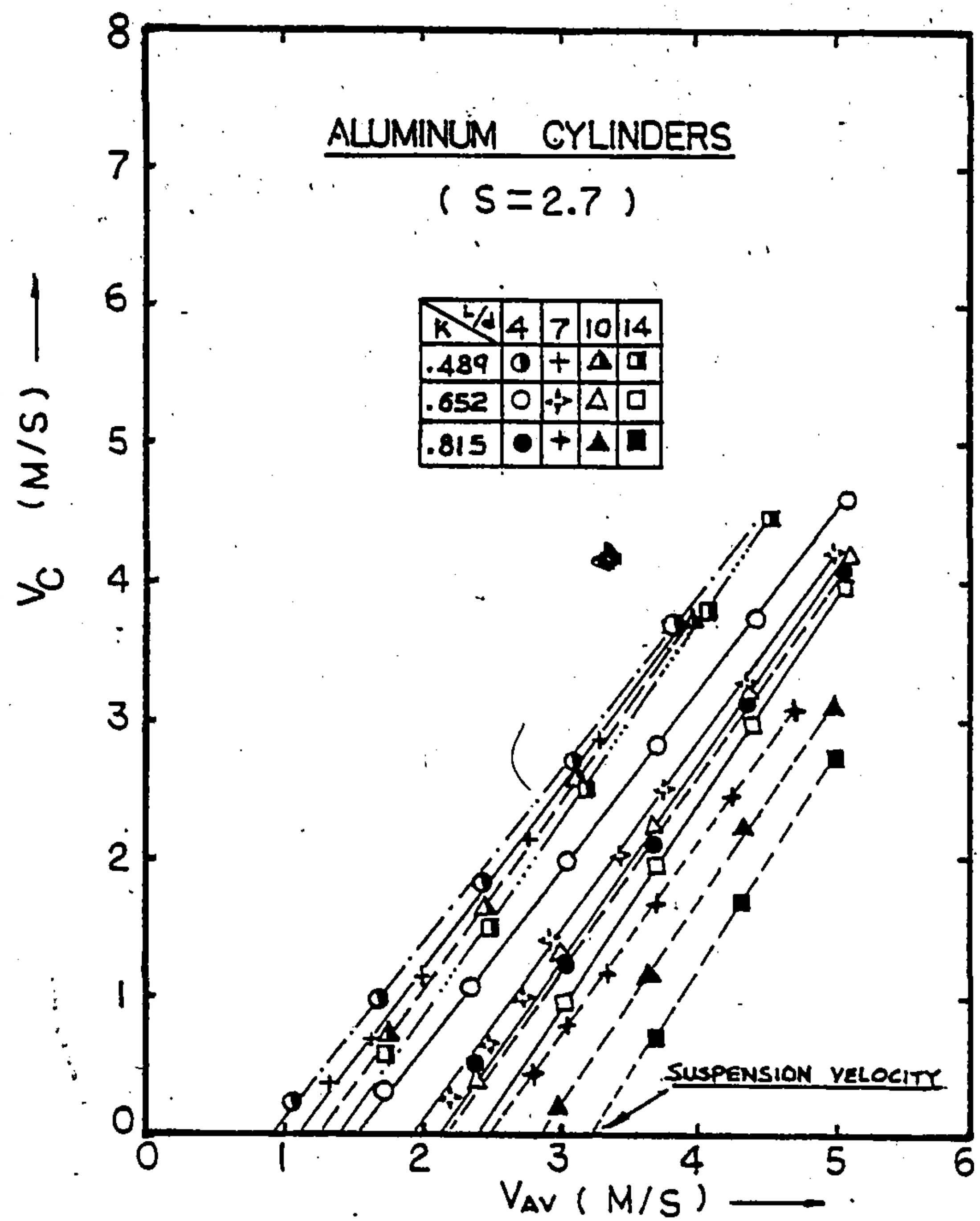
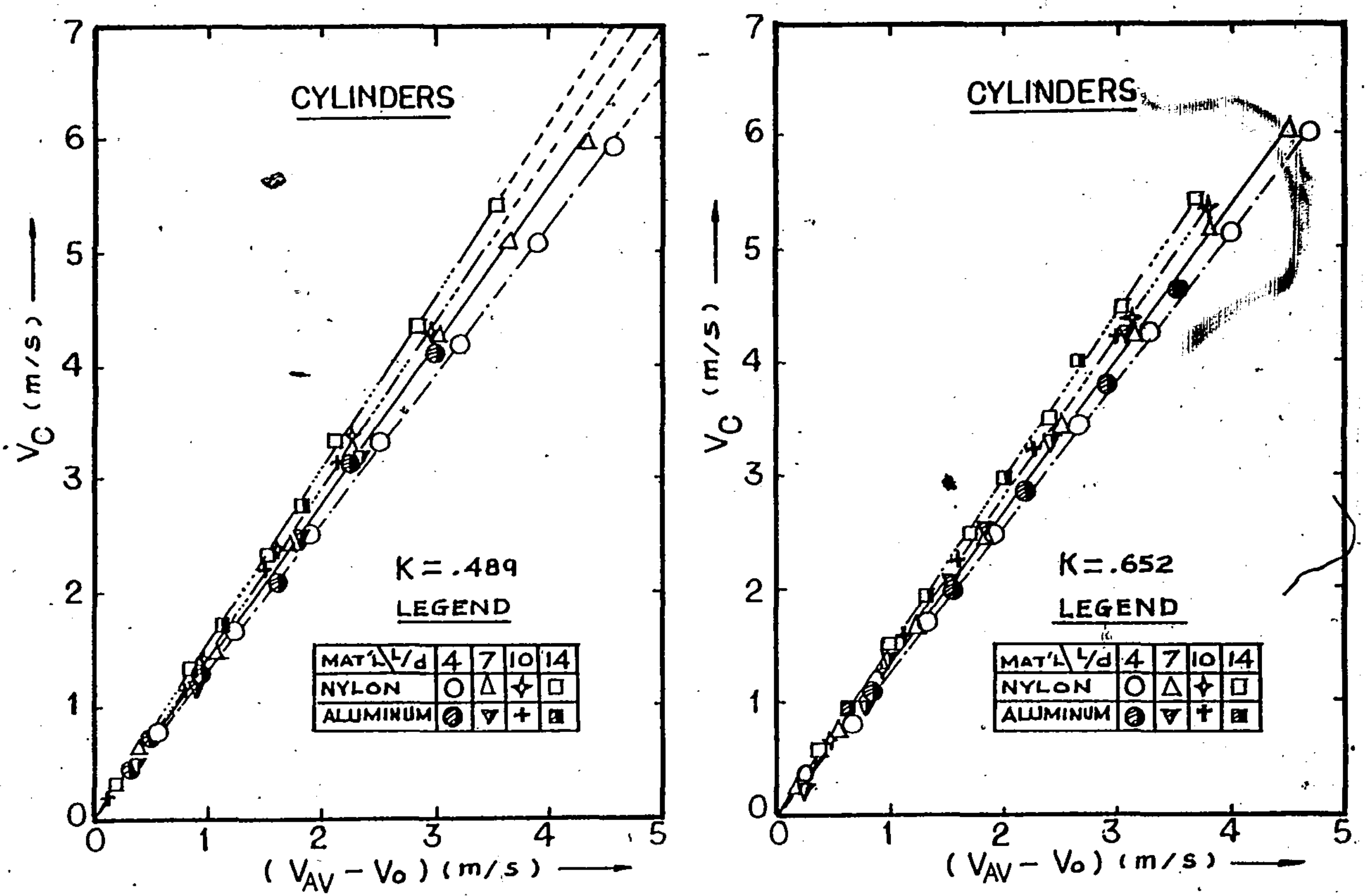


FIG. (6.16): THE VARIATION OF V_C WITH V_{AV}: ALUMINUM CYLINDERS



FIGURES (6.17, 18): THE LINEAR RELATIONSHIP BETWEEN V_C AND $(V_{AV} - V_o)$: CYLINDERS

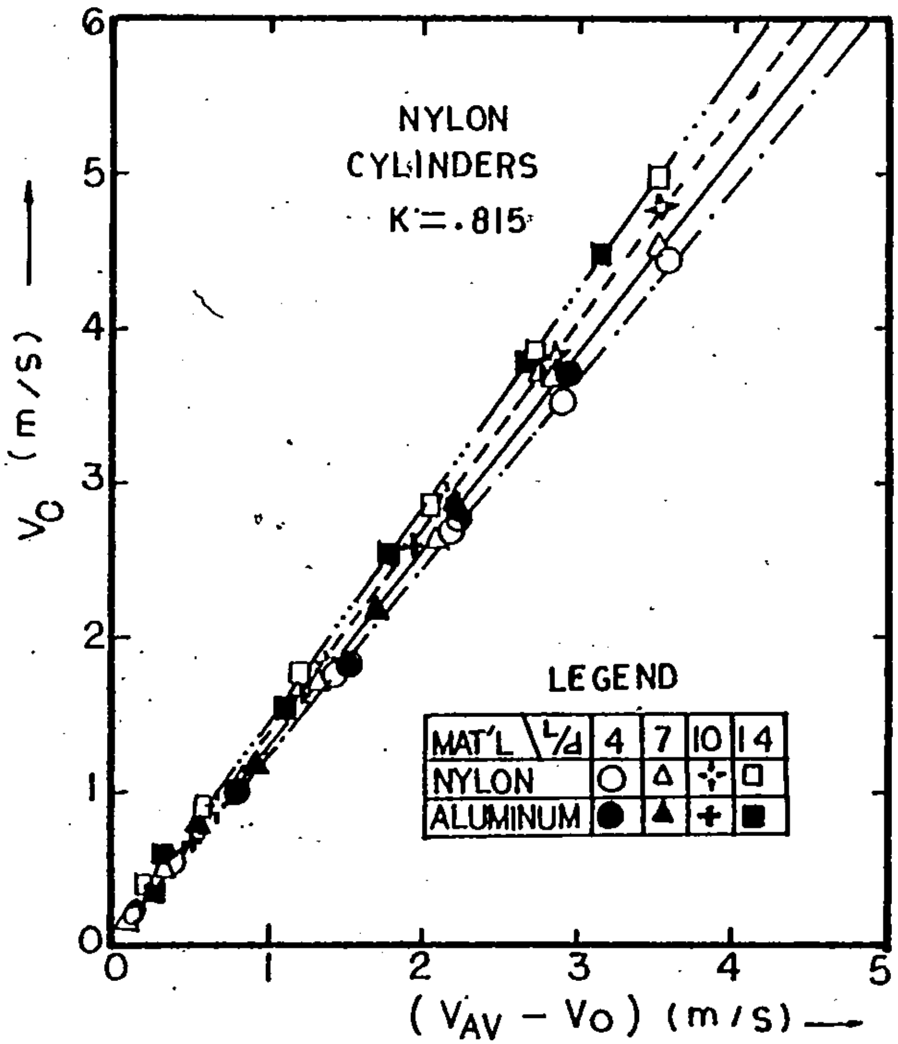


FIG. (6.19) THE LINEAR RELATIONSHIP BETWEEN V_C AND $(V_{AV} - V_o)$

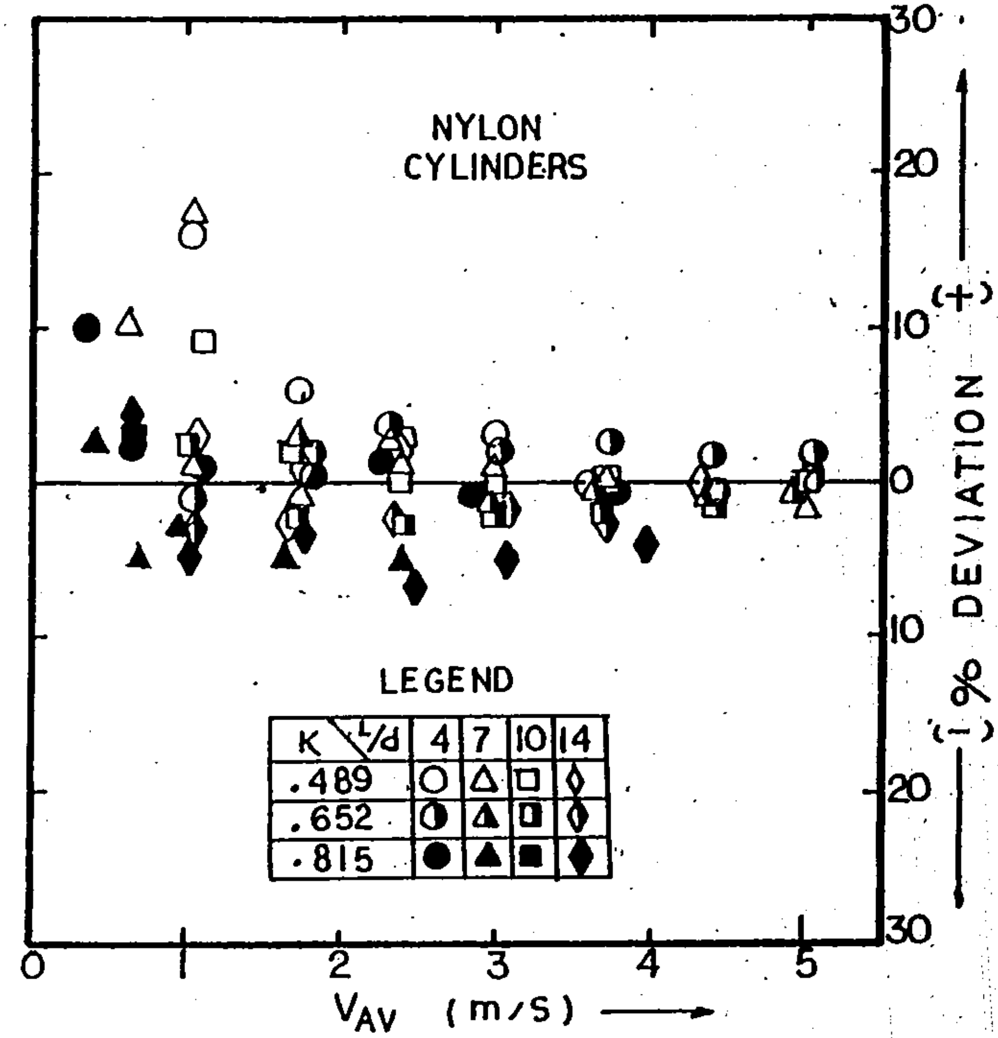


FIG. (6.20) THE DEVIATION OF EXPERIMENT FROM EQ^n. (6.5) FOR NYLON CYLINDERS

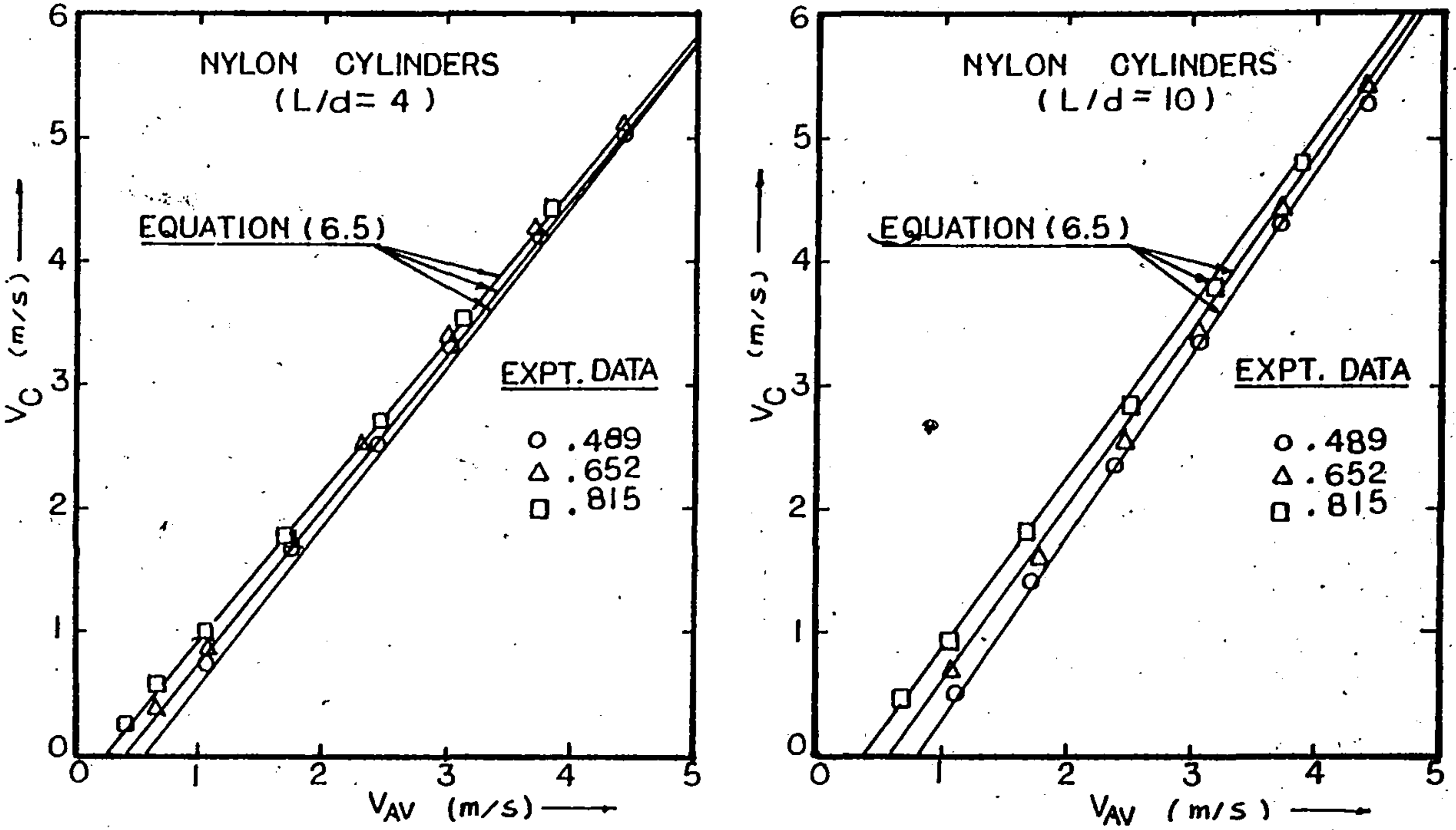
In order to find the suspension velocity, V_o, Equation (3.13) is used, which is

$$V_o = \sqrt{2gD(S_c-1)}\,(1-K^2)(L/d)^a(K)^b \qquad (3.13)$$

In order to find the values of a and b, the experimental values of V_o, obtained from Figures 6.12 to 6.16 were fitted into Equation (3.13) using a mini-computer. The final equation for V_o is found to have the following form:

$$V_o = \sqrt{2gD(S_c-1)}\,(1-K^2)(L/d)^{0.37}\left(1-\frac{1}{S_c}\right)^{0.05} \qquad (6.4)$$

The addition of the term $\left(1-\frac{1}{S_c}\right)^{0.05}$ to Equation (6.4) is intended to take account of the surface roughness effect which was found to increase with density in the experiments. Good agreement between the experimental and the predicted values given by Equation (6.4) was found. In order to verify Equation (6.4), data from Lee's work (23) have been used. It was found that the predicted values were 15 - 20% larger than the measured values. This deviation may be due to the fact that the values of V_o used in establishing Equation (6.4) were larger than the actual suspension velocities. Close examination of the data points presented in Figures 6.12 to 6.16 for very low V_c has revealed that the slopes of the curves are usually smaller in low V_{av} than that in medium and high V_{av}, consequently, the extrapolated values which gave the suspen-



FIGURES (6.21, 22) COMPARISON OF EQN.(6.5) AND EXPERIMENT FOR NYLON CYLINDERS

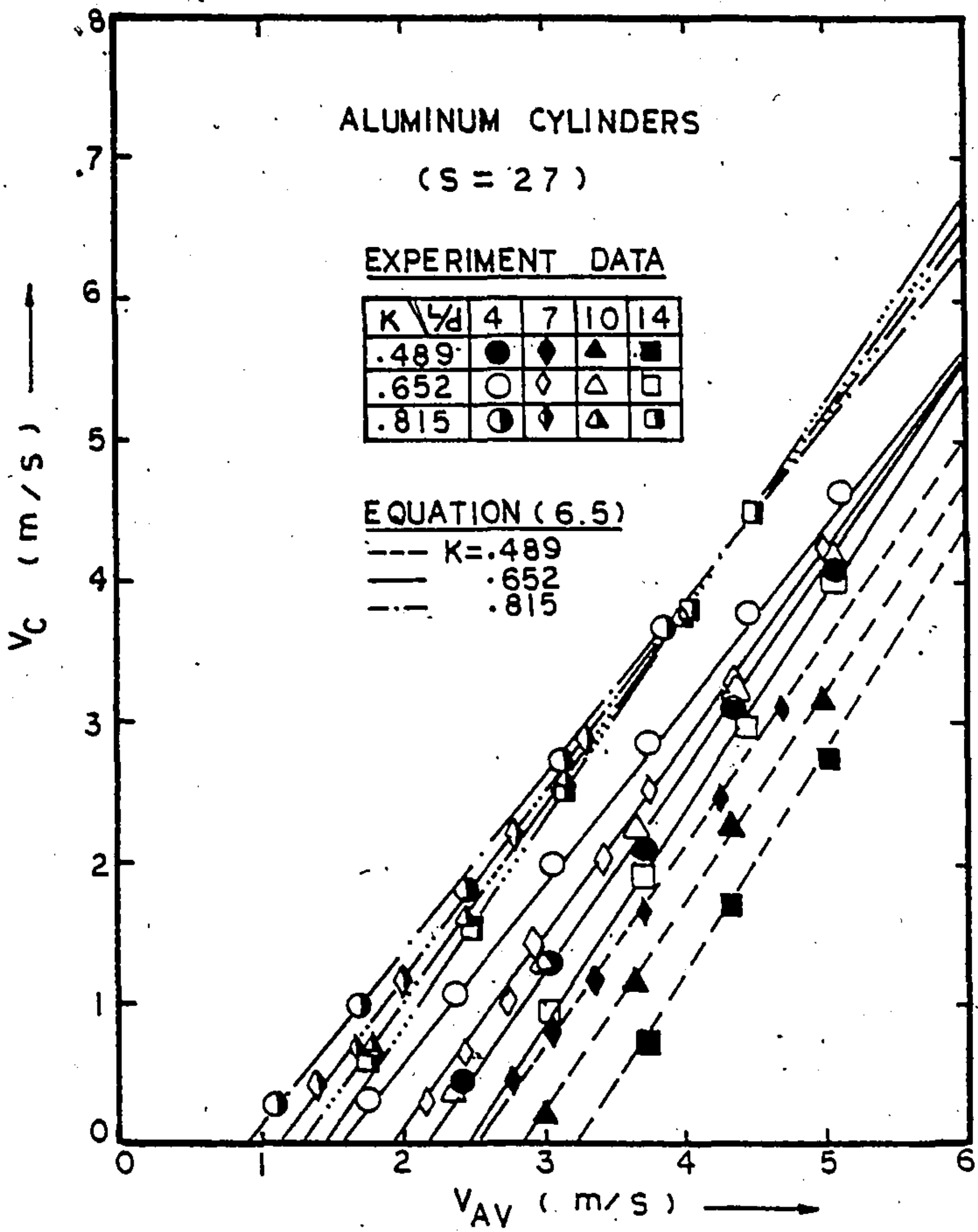


FIG. (6.23): COMPARISON OF EQUATION (6.5) WITH EXPERIMENT: AL. CYLINDERS sion velocities, were larger than the actual values.

By substituting Equation (6.4) into Equation (6.3c) and after rearranging, the following semi-empirical correlation for V_c is obtained.

$$V_c = \frac{1}{K^{0.128}}\left[(L/d)^{0.128} V_{av} - \sqrt{2gD(S_c-1)(L/d)}\,(1-K^2)(1-\frac{1}{S_c})^{0.05}\right] \quad (6.5)$$

Figure (6.20) shows the percentage discrepancy between the experimental values and the values predicted by Equation (6.5). Figures (6.21) to (6.23) show graphs of the experimental data together with Equation (6.5) These graphs show that Equation (6.5) is especially good in the range of medium and high V_{av}'s.

6.2.2 Spheres

The procedure employed to establish the correlation between V_c and V_{av} for spheres is similar to that used for cylinders. Again, a linear relationship between V_c and $(V_{av}-V_o)$ is obtained, (Figure 6.24), i.e.

$$V_c = m(V_{av} - V_o) \quad (6.6)$$

The slope m of the V_c versus $(V_{av}-V_o)$ curves was found to obey the following relationship:

$$m = \frac{1}{K^{0.34}} \quad (6.7)$$

The value of the constant C in Equation (3.14) which is the equation for the suspension velocity for spheres, is found to have the value of -0.5. Equation (3.14)

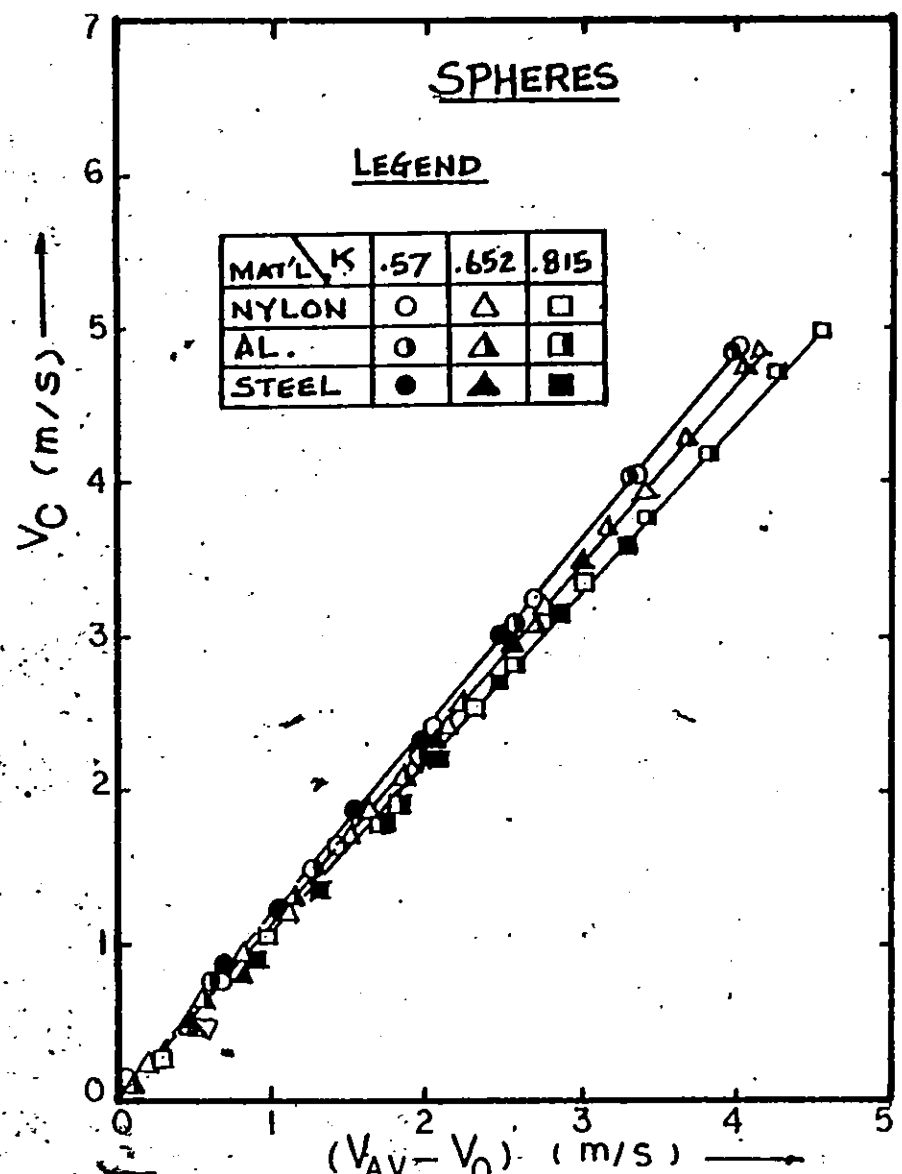


FIG.(6. 24): THE LINEAR RELATIONSHIP BETWEEN V_C AND $(V_{AV} - V_o)$: SPHERES

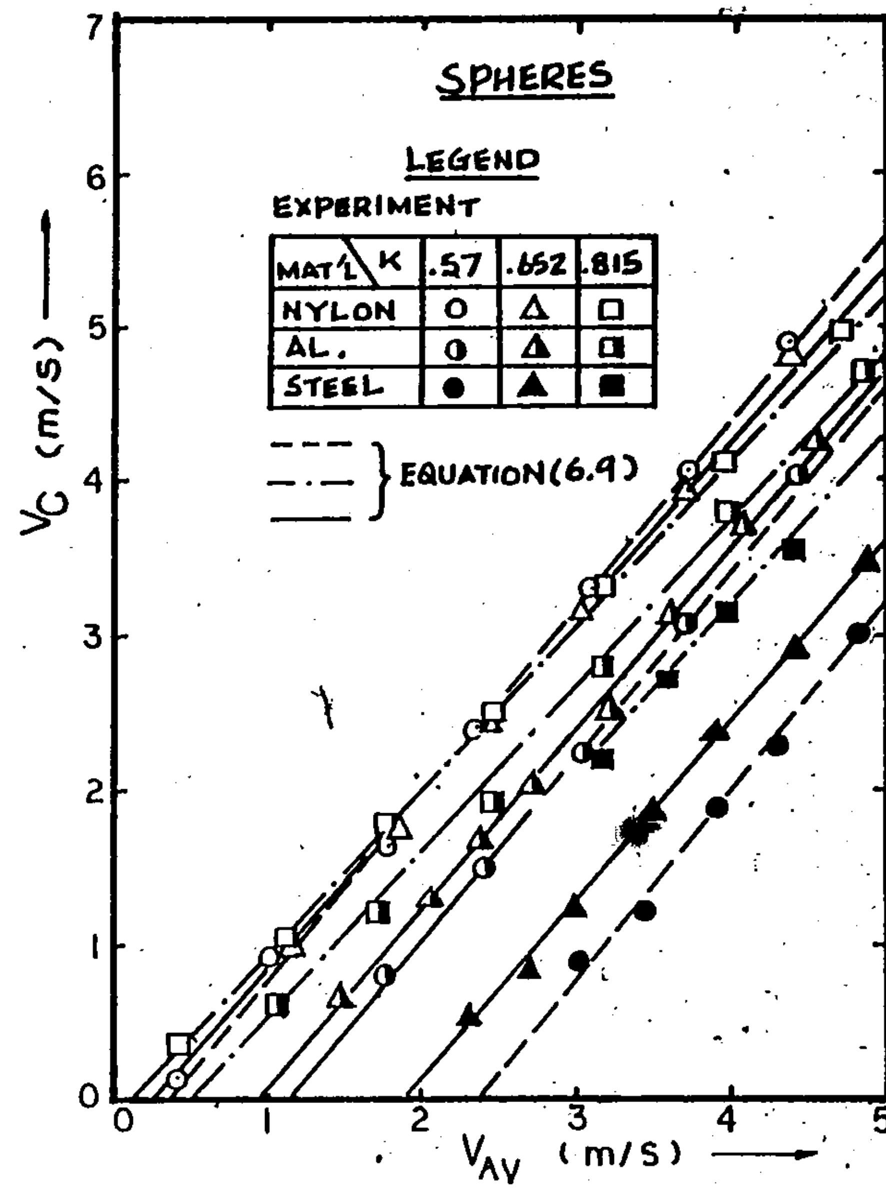


FIG. (6.25) : COMPARISON OF EQN.(6.9) AND EXPERIMENT : SPHERS

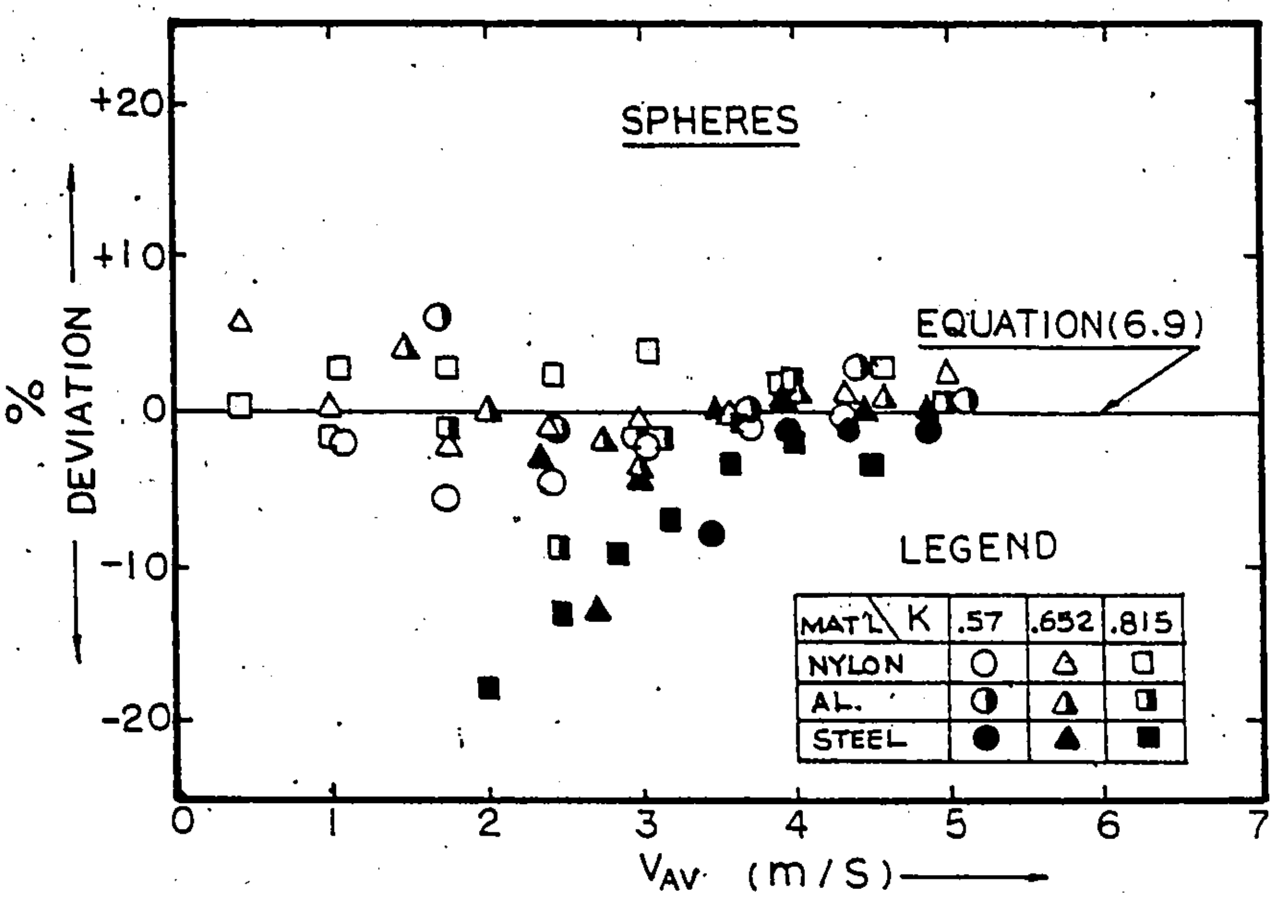


FIG. (6.26) THE DEVIATION OF EXPERIMENT FROM EQUATION (6.9) then is re-written as:

$$V_o = \sqrt{\tfrac{4}{3}gD(S-1)/K}\,(1-K^2) \qquad (6.8)$$

The empirical correlation for predicting V_c for spheres was found to be

$$V_c = \frac{1}{K^{0.34}}\left[V_{av} - \sqrt{\tfrac{4}{3}gD(S_c-1)/K}\,(1-K^2)\left(1-\frac{10}{S_c}\right)^{0.05}\right] \qquad (6.9)$$

It is interesting to note the striking resemblence between Equations (6.9) and (6.5).

The values of V_c predicted by Equation (6. 9) together with the experimental data are plotted in Figure 6.25 against V_{av}, and the percentage deviation of the experimental results from Equation (6.9) is shown in Figure (6.26). Good agreement between the experimental and generated data is shown by these graphs.

6.3 The Variation of Pressure Ratio, R_p

The pressure ratio, R_p, which is defined as the ratio of the capsule pressure gradient, $(\Delta P/L)_c$, to the pressure gradient, $(\Delta P/L)_L$, required in the free pipe for the same average velocity, is a convenient comparison of the energy consumption for the capsule flow to that for the free pipe flow of the same flow rate.

A dimensional analysis shows that R_p is a function of four independent variables: V_{av}, K, L/d and $(\sigma-\rho)/\rho$, which are the same variables as those used for the velocity ratio. The individual effects of these four variables on

R_p are discussed in the following sections.

6.3.1 Cylindrical Capsules

The variation of R_p with V_{av} for cylinders is presented in Figure (6.27). The resulting curves may be regarded as characteristic for capsule flow since they illustrate the effects of the different independent variables on R_p. It is apparent that, as V_{av} increases, R_p decreases at a faster rate initially but tends to become constant later at high V_{av}'s for nylon cylinders, although for aluminum cylinders R_p continues to decrease at the highest V_{av} investigated. A decrease in R_p with an increase in V_{av} is to be expected since for a capsule in suspension, V_{av} is small resulting in a small $(\Delta P/L)_L$ which is much smaller than the required $(\Delta P/L)_c$ for the particular capsule. As V_{av} is increased, however, $(\Delta P/L)_L$ increases in proportion to the applied $(\Delta P/L)_c$ thereby reducing R_p. The tendency of R_p to become constant at high V_{av} is also to be expected, because if Equation (5.4), which defines that $(\Delta P/L)_c$ is the sum of $(\Delta P_o)_L$ and $(\Delta P/L)_L$, is divided by $(\Delta P/L)_c$, it becomes

$$R_p = (\Delta P_o/L)/(\Delta P/L)_L + 1 \qquad (6.10)$$

Experimental results have shown that $(\Delta P_o/L)$ is relatively invariant with V_{av} (Figure 6.28). $(\Delta P/L)_L$, however, is proportional to the square of V_{av}. Hence the

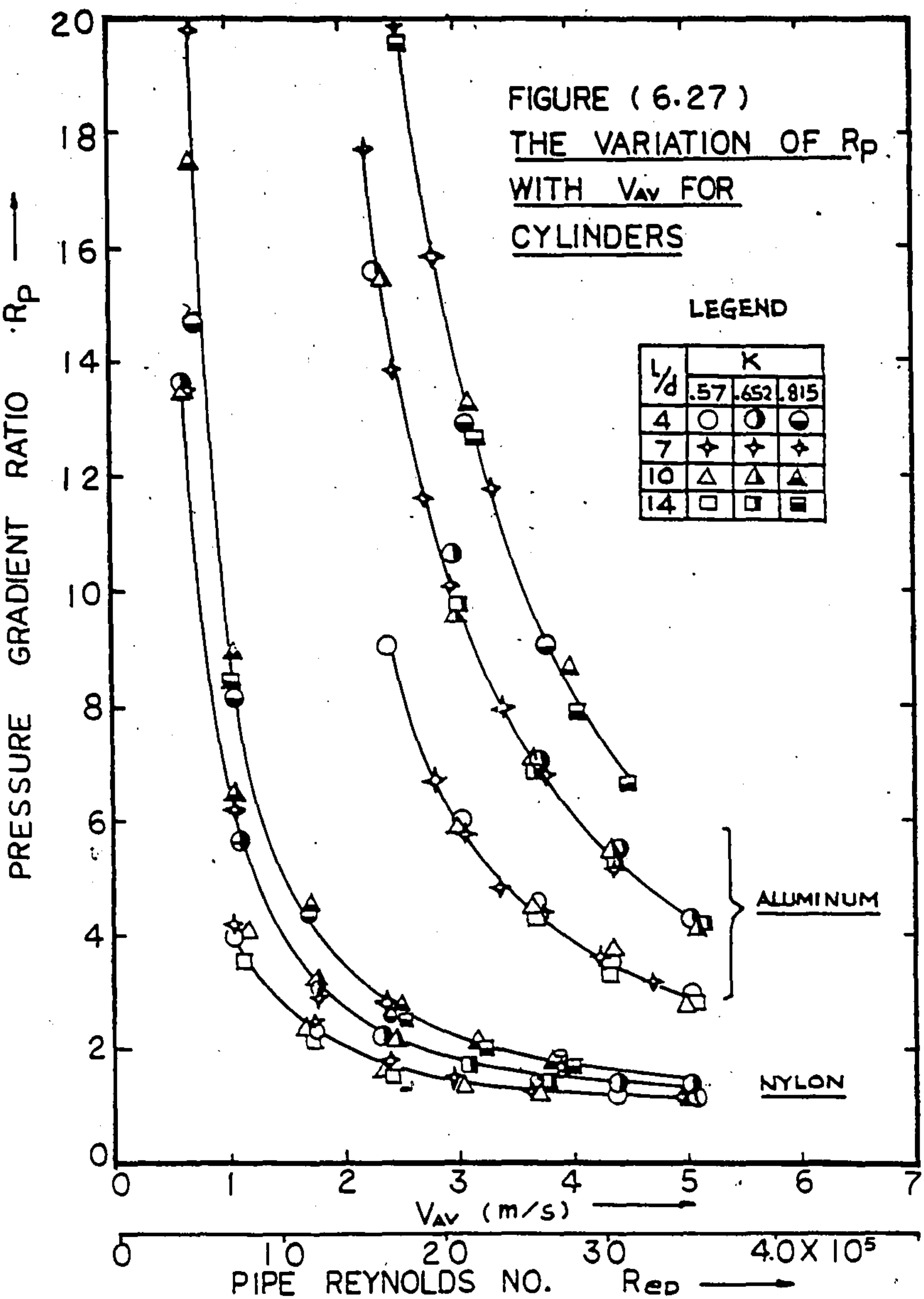
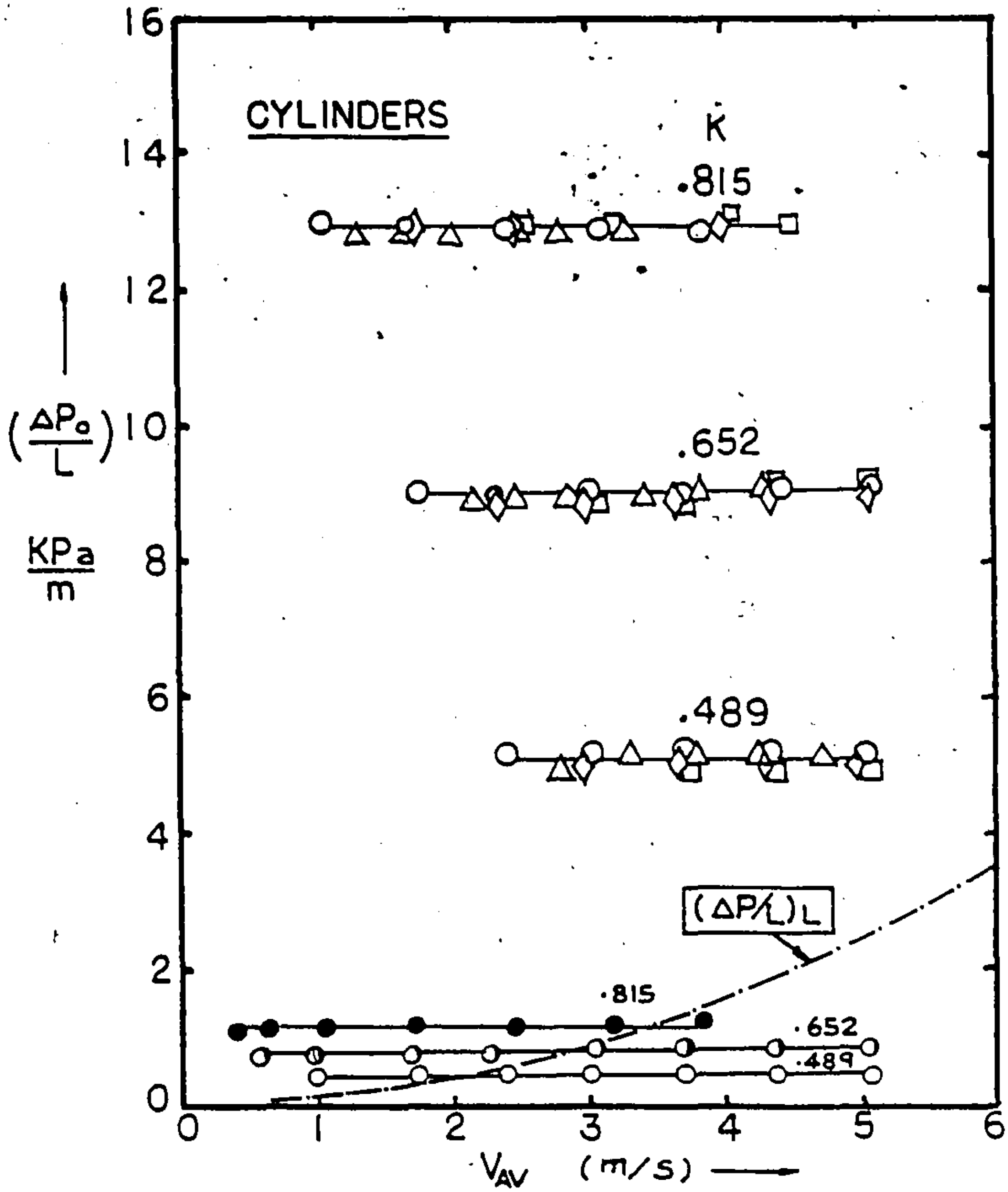


FIGURE (6.27)
THE VARIATION OF Rp WITH VAV FOR CYLINDERS
LEGEND
L/d
K
.57
.652
.815
4
7
10
14
ALUMINUM
NYLON
PRESSURE GRADIENT RATIO Rp
VAV (m/s)
PIPE REYNOLDS NO. Red
0
2
4
6
8
10
12
14
16
18
20
1
3
5
7
1.0
2.0
3.0
4.0 X 10^5



FIGURE(6.28) THE VARIATION OF $(\Delta P_o/L)$ AND $(\Delta P/L)_L$ WITH V_{AV} : CYLINDERS

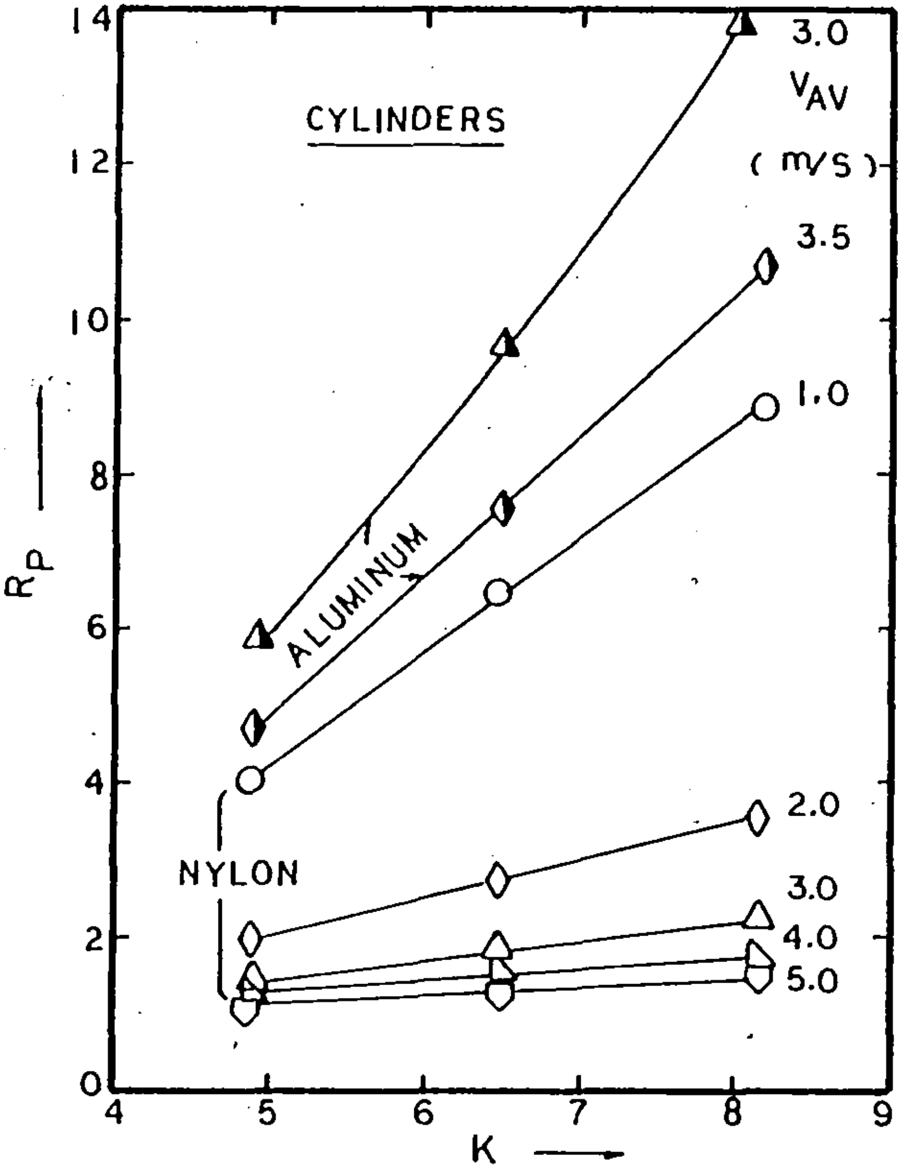


FIG. (6.30): R_P VS. K : CYLINDERS

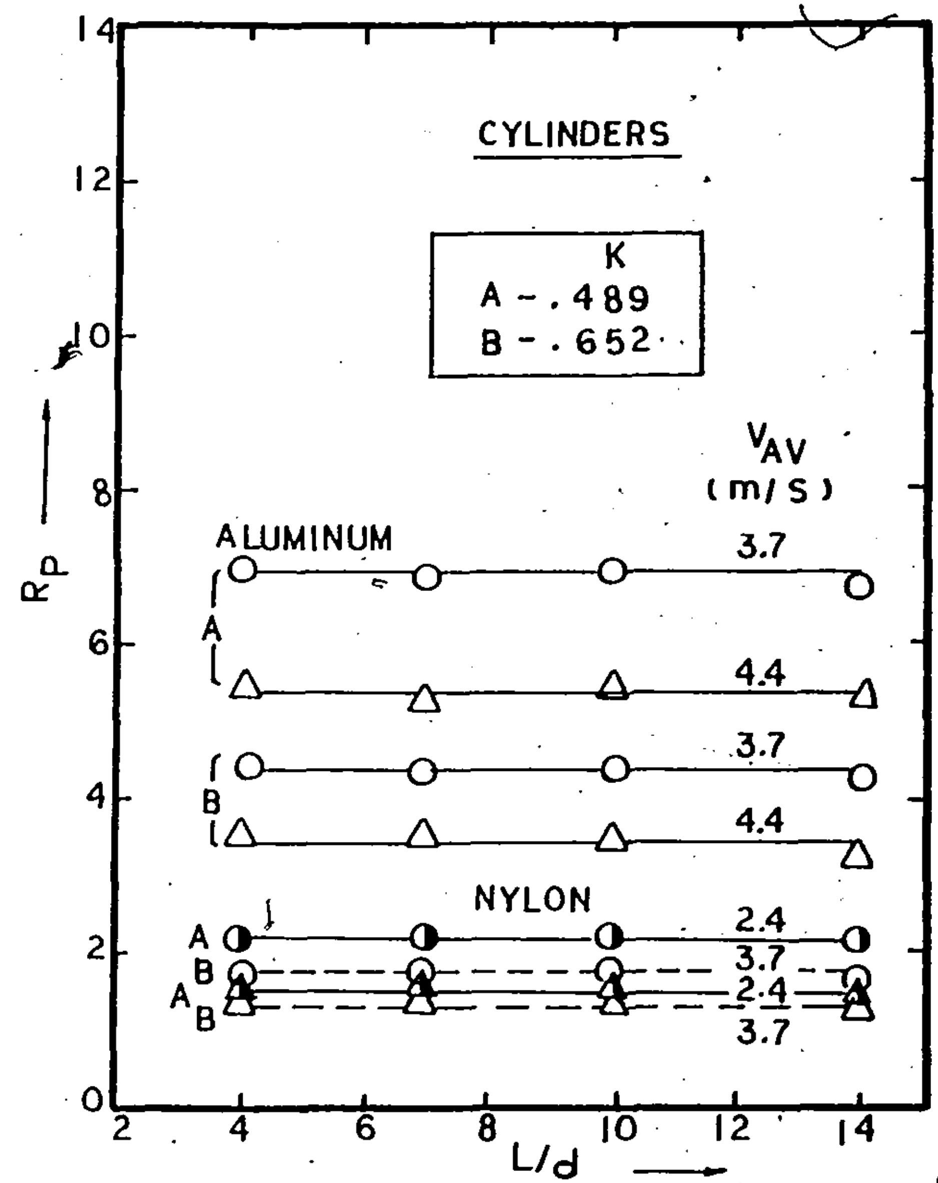


FIG. (6.29): R_P VS. L/d : CYLINDERS significance of $(\Delta P_o/L)/(\Delta P/L)_L$ decreases as V_{av} increases, resulting in R_p approaching a constant value.

Figure 6.27 indicates there is almost no effect of L/d ratio on R_p, and most of the data for a given diameter capsule may be correlated with a single curve irrespective of L/d. The same result is observed on a plot of R_p versus L/d (Figure 6.29), in which the curve for any given diameter capsule at any V_{av} is a horizontal line. This indicates that the end effects (if there are any) are negligibly small for the L/d range used in the experiments.

The effect of the diameter ratio, K, on R_p is shown in Figure 6.30 for various V_{av}'s. As may be expected, R_p increases with an increase of K at any particular V_{av}. Obviously the capsule pressure gradient $(\Delta P/L)_c$ increases as K is increased because of the increase of capsule base area. However, since the pressure gradient, $(\Delta P/L)_L$, required for the same flow rate through a free pipe is independent of K, R_p increases with an increase in K for a fixed V_{av}. The effect of K on R_p noticeably decreases as V_{av} is increased. For example, consider the nylon cylinders, by varying the value of K from 0.489 to 0.815 at V_{av} = 1.0 m/s, the variation of R_p is from 4.0 to 9.0 which represents an increase in R_p of 225 %. While at V_{av} = 5.0 m/s the increase in R_p is only 36%. The reason for the decreasing effect of increasing K on R_p as V_{av} increases, is again related to the fact that the significant term $(\Delta P_o/L)(\Delta P/L)_L$ in Equation (6.10) approaches zero as $V_{av} \rightarrow \infty$.

Figure 6.27 also shows the effect of density on R_p. An increase in R_p with an increase of (S_c-1) is to be expected since a denser or heavier capsule requires a larger $(\Delta P/L)_c$ at any particular V_{av}.

The effects of the four independent variables on R_p may be summarized as follows: R_p decreases with an increase in V_{av} but increases with an increase in K and (S_c-1), and there is essentially no effect of L/d on R_p.

6.3.2 Spherical Capsules

Since only single spheres were used in the experiments, it was virtually impossible to accurately measure $(\Delta P)_c$ across a sphere other than the steel ones because it was very small for nylon and aluminum spheres.

Figure 6.31 gives a plot of R_p versus V_{av} for the steel spheres for K's of 0.57, 0.652 and 0.815. From which it can be observed that R_p decreases with an increase in V_{av} and increases with increasing K, the same trend as in the case of cylindrical capsules.

6.4 Correlations for the Prediction of $(\Delta P/L)_c$

Due to the fact that only a limited amount of data for spherical capsules was obtained, the correlations for predicting $(\Delta P/L)_c$ presented are only for the cylindrical capsules.

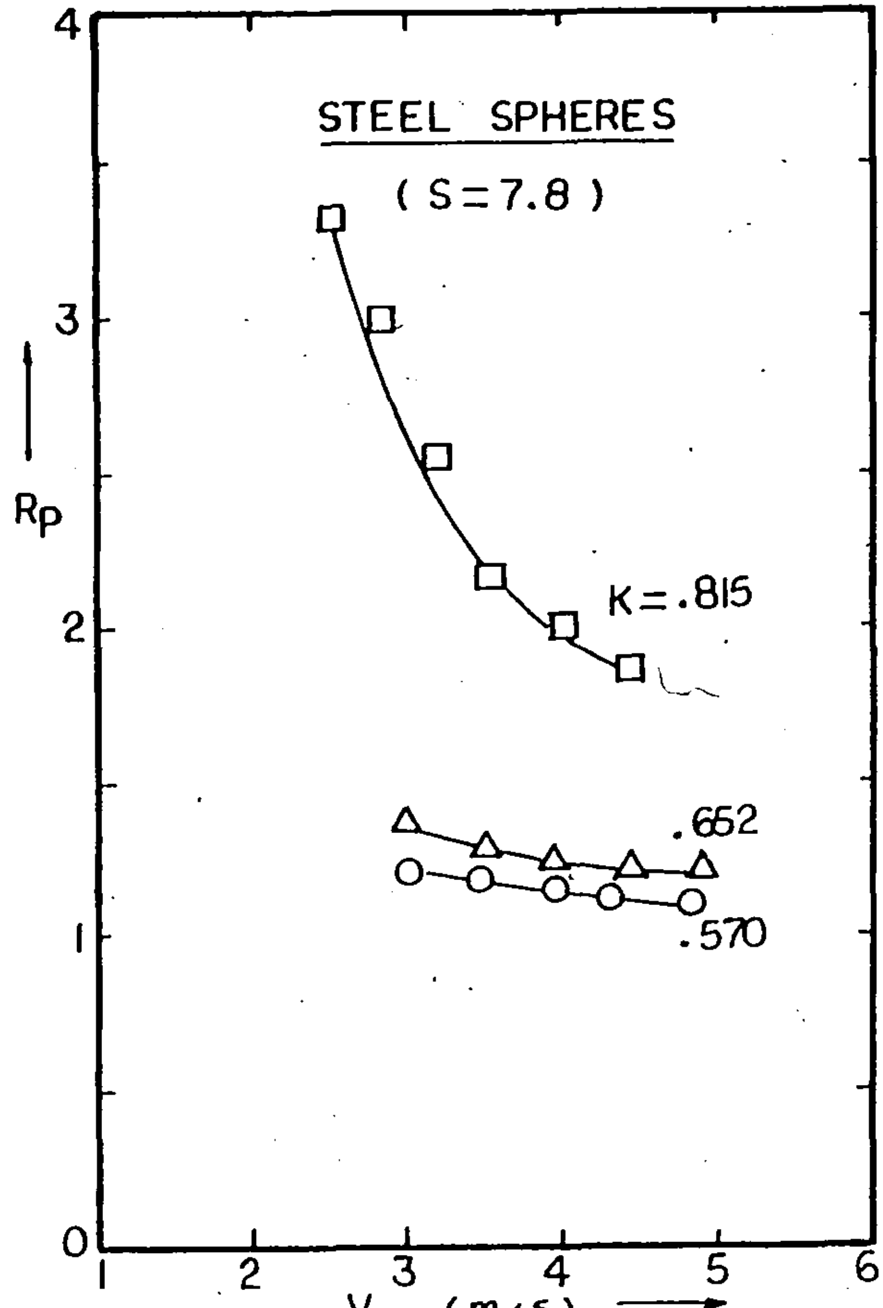


FIG. (6.31) R_P VS. V_{AV} FOR STEEL SPHERES

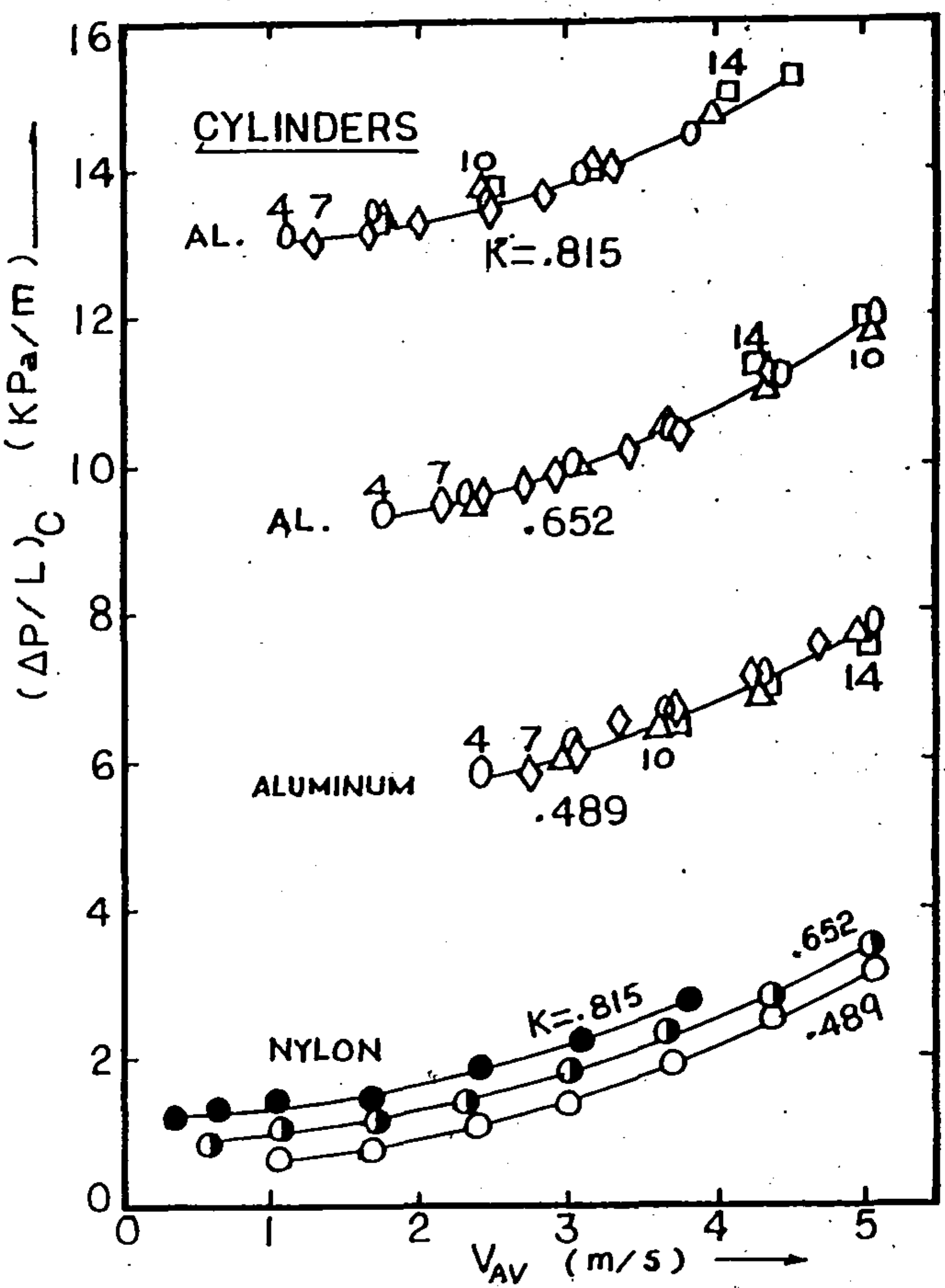


FIG. (6.32) THE VARIATION OF CAPSULE PRESSURE GRADIENT WITH V_{AV}: CYLINDERS

The variation of the total pressure gradient across the cylinders, $(\Delta P/L)_c$, with V_{av}, K and L/d is presented in Figure 6.32. It can be seen that all the curves have the same shape and that $(\Delta P/L)_c$ increases with V_{av} and K but is virtually independent of L/d. This implies that a single equation for correlating the data of $(\Delta P/L)_c$ as a function of K and V_{av} may exist.

It has been mentioned in Chapter 5 that $(\Delta P/L)_c$ consists of two components: $(\Delta P_o/L)$ - the increase in pressure gradient due to the presence of the capsule in the test section and $(\Delta P/L)_L$ - the free pipe pressure gradient due to the fluid alone. That is

$$(\Delta P/L)_c = (\Delta P_o/L) + (\Delta P/L)_L \qquad (5.4)$$

These two components have been separately plotted against V_{av} in Figure 6.28 which shows that $(\Delta P_o/L)$ is a function of K only and that $(\Delta P/L)_L$ at any particular V_{av} is the same for every capsule. Based on this fact we may treat these two pressure components separately. The compoent $(\Delta P_o/L)$ may be determined empirically, and $(\Delta P/L)_L$ can be predicted using standard procedures for pipe flow.

a) Correlation of $(\Delta P_o/L)$

In Chapter 3, an empirical correlation was presented for the prediction of the pressure gradient due to the capsule alone, of the form

$$\frac{(\Delta P_o/L)}{(\sigma-\rho)g} = CK^q \qquad (3.19)$$

or $p^* = CK^q$ (6.11)

where C and q are universal constants to be determined empirically.

In logarithm form Equation (6.11) is written as

$$\ell n\, P^* = \ell n C + q \ell n K \qquad (6.12)$$

Equation (6.11) expresses the linear relation between the pressure function P* and K, hence a straight line is obtained when P* is plotted against K on a logarithmic plot as shown in Figure (6.33) for both nylon and aluminum cylinders. Since $(\Delta P_o/L)$ is virtually invariant with V_{av} (cf. Figure 6.28) a single point is obtained in the graph for a given cylinder of constant L/d and K. Figure 6.33 reveals that a single line is adequate to express Equation (6.12) and the same values of C and q are for both the nylon and aluminum cylinders.

Using linear regression the present data for cylinders were fitted with Equation (6.12) and the constant C and q were found.

The resulting fitted equation for cylinders is

$$(\Delta P_o/L) = 1.15\,(K)^{1.84}\,(\sigma-\rho)g \qquad (6.13)$$

b) Correlation of $(\Delta P/L)_L$

In steady incompressible pipe flow, the equation generally adopted for the calculation of the friction loss due to the pipe wall is the Darcy-Weisbach equation:

$$(\Delta P/L)_L = f\frac{\rho V_{av}^2}{2D} \qquad (6.14)$$

where f is the friction factor of the pipe wall.

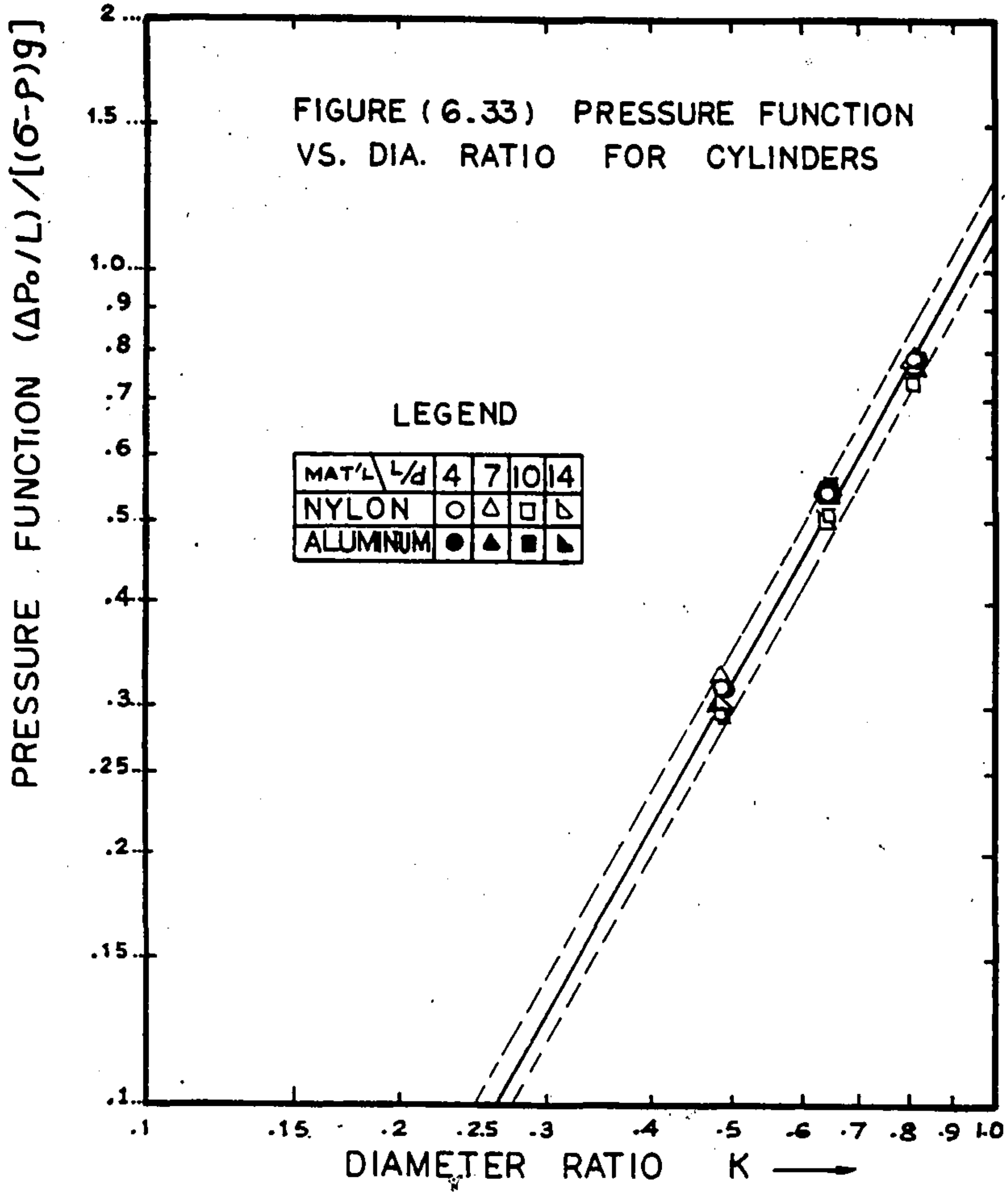


FIGURE (6.33) PRESSURE FUNCTION VS. DIA. RATIO FOR CYLINDERS
LEGEND
MAT'L \ L/d 4 7 10 14
NYLON
ALUMINUM
PRESSURE FUNCTION (ΔPo/L)/[(σ-ρ)g]
2
1.5
1.0
.9
.8
.7
.6
.5
.4
.3
.25
.2
.15
.1
.1
.15
.2
.25
.3
.4
.5
.6
.7
.8
.9
1.0
DIAMETER RATIO K

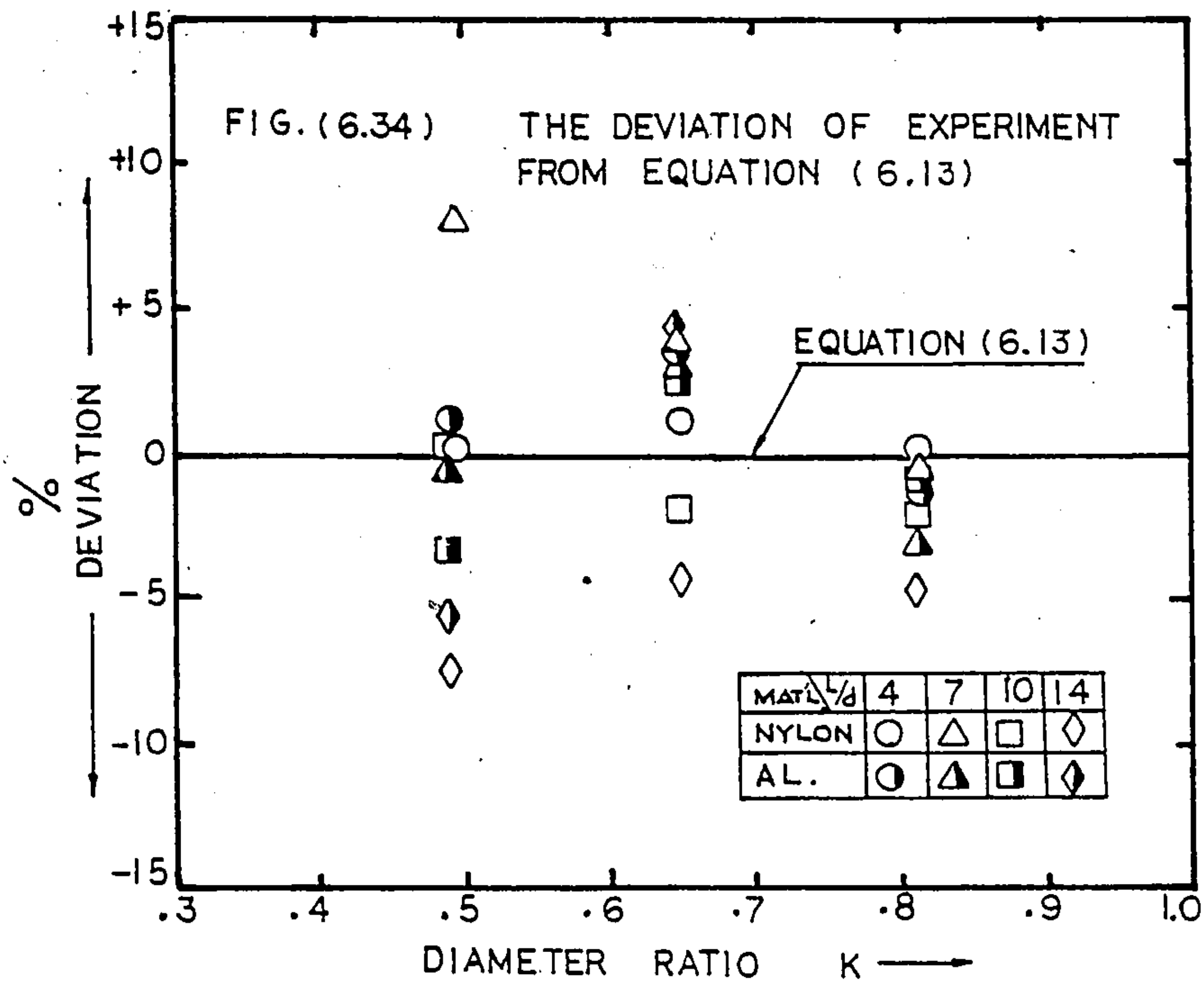


FIG. (6.34) THE DEVIATION OF EXPERIMENT FROM EQUATION (6.13)
EQUATION (6.13)
% DEVIATION
+15
+10
+5
0
-5
-10
-15
.3
.4
.5
.6
.7
.8
.9
1.0
DIAMETER RATIO K
MAT'L L/d
4
7
10
14
NYLON
AL.

There are a number of empirical correlations available in the open literature for the calculation of f. Among them the one developed by Colebrook (44) for flow in commercial pipes was chosen for the present purpose, i.e.

$$\frac{1}{\sqrt{f}} = -0.86 \ \ln \left[\frac{\varepsilon/D}{3.7} + \frac{2.51}{R_e\sqrt{f}}\right] \qquad (6.15)$$

where ε/D is the ratio of the roughness of the pipe wall to the pipe diameter. In the present experiment $\varepsilon/D = 0.0002$ was adopted.

With f calculated from Equation (6.15), $(\Delta P/L)_L$ for a given V_{av} can be determined from Equation (6.14).

By means of Equations (6.13) and (6.14) the pressure gradient across a capsule can be predicted.

A complete calculation of $(\Delta P/L)_c$ by using Equations (6.13) and (6.14) together with the experimental results is listed in Appendix (D). A comparison of the results indicates that the majority of the calculated values of $(\Delta P/L)_c$ do not deviate from the experimental results more than $\pm 5\%$.

Lastly the percentage deviation of the experimental results from Equation (6.13) for the cylinders is shown in Figure 6.34 which indicates that the majority of the data are within the range of $\pm 5\%$ of the fitted equation and that the chosen pressure function is less accurate as K decreases.

6.5 Energy Requirements

The energy consumption for capsule transport is given by the relation

$$E = (\Delta P/L)_c \, Q_w \qquad (6.16)$$

where E is in kilowatt per meter (KW/m), $(\Delta P/L)_c$ and Q_w are in KN/m^3 and m^3/s respectively.

The unit energy requirement based on the volumetric rate of capsule is

$$E/\dot{V} = (\Delta P/L)_c \left(\frac{D}{d}\right)^2 \left(\frac{V_{av}}{V_c}\right) \frac{KW/m}{m^3/s} \qquad (6.17)$$

The unit energy requirement based on the mass rate of the capsule is

$$\underline{P} = E/\dot{m} = (\Delta P/L)_c \left(\frac{D}{d}\right)^2 \left(\frac{V_{av}}{V_c}\right) \frac{1}{\sigma} \; \frac{KW/m}{kg/s} \qquad (6.18)$$

Figure 6.35 presents a graph of P versus V_{av} to show the variation of P with V_{av}, K and L/d for nylon cylinders, in which, for clearity, only the curves for L/d = 7 are shown. The curves show that P first decreases to a minimum at values of V_{av} for which R_v is unity and then increases with increasing V_{av}. The reason for this behaviour is that at low V_{av} the ratio $(\frac{V_{av}}{V_c}) \rightarrow \infty$; V_c being very small. However a finite and relatively large $(\Delta P/L)_c$ is required even at very low V_{av} for any cylindrical capsules, consequently a very high value of P results under this condition. As V_{av} increases, the ratio $(\frac{V_{av}}{V_c})$ decreases at a faster rate than the increase in $(\Delta P/L)_c$ when $R_v < 1.0$ (cf Figures

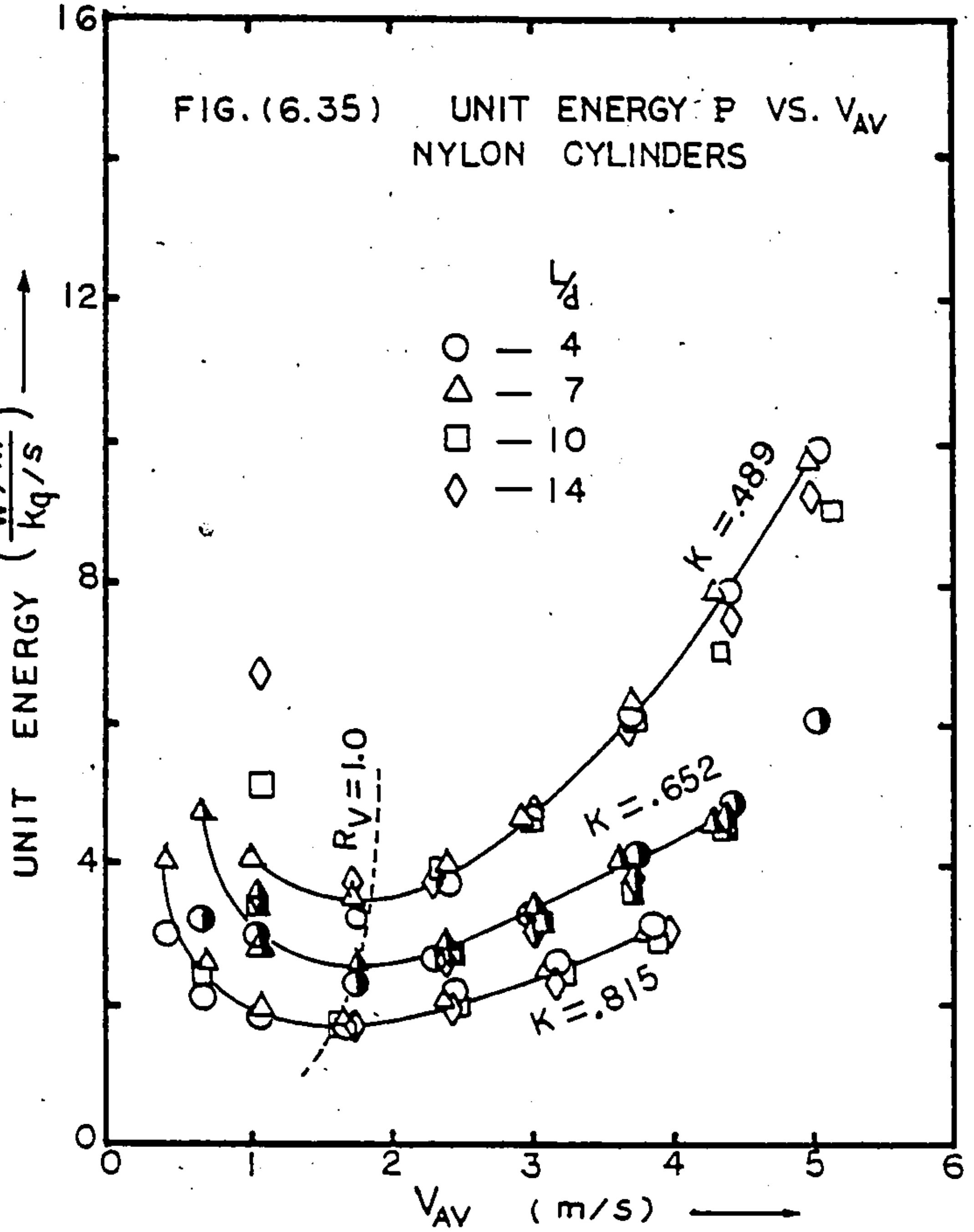


FIG. (6.35) UNIT ENERGY P VS. V_{AV}
NYLON CYLINDERS
L/d
○ — 4
△ — 7
□ — 10
◇ — 14
K = .489
K = .652
K = .815
$R_V = 1.0$
UNIT ENERGY (W/m / Kg/s)
V_{AV} (m/s)
0
4
8
12
16
0
1
2
3
4
5
6

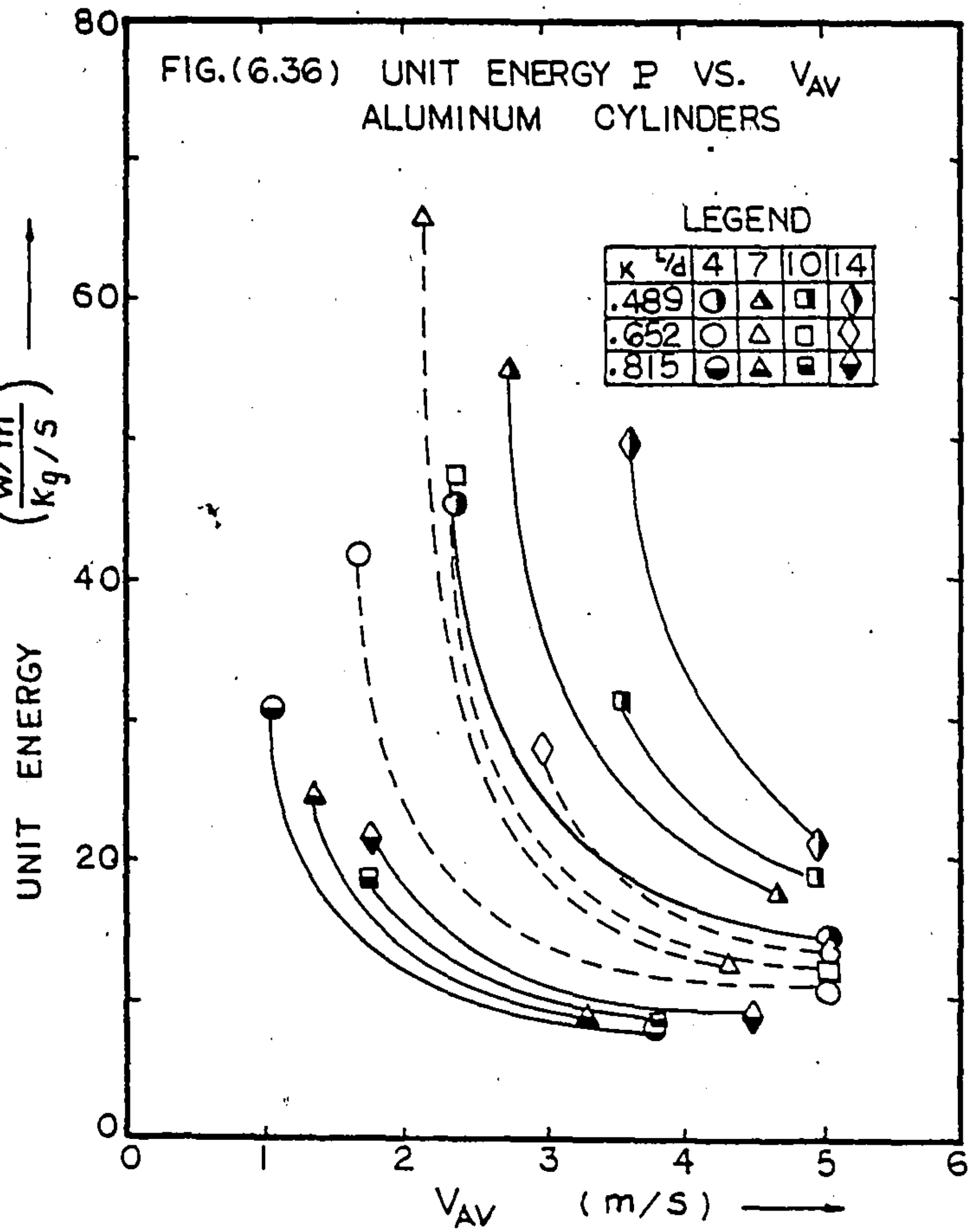


FIG.(6.36) UNIT ENERGY P VS. V_{AV}
ALUMINUM CYLINDERS
LEGEND
K L/d 4 7 10 14
.489
.652
.815
UNIT ENERGY (W/m / Kg/s)
V_{AV} (m/s)
0 20 40 60 80
0 1 2 3 4 5 6

6.1, 2, and 32), therefore, the required P decreases with increaase of V_{av} in this velocity range. On the other hand, when $R_v > 1.0$, $\frac{V_c}{V_{av}}$ tends to become constant so does the ratio of (V_{av}/V_c). However $(\Delta P/L)_c$ continuously increases as V_{av} increases, thereby an increasing P results. Figure 6.36 is a similar plot of P versus V_{av} for aluminum cylinders. Since none of the aluminum cylinders ever reached the condition for $R_v > 1.0$, P always decreases with increasing V_{av} for these cylinders.

The effect of L/d on P is also shown in Figure 6.35 and 6.36. Figure 6.35 shows that as L/d is increased P increases when $R_v < 1.0$, but it is the reverse when $R_v > 1.0$, i.e. P decreases. The reason for such behaviour is due to the fact that $(\Delta P/L)_c$ is constant for constant K capsules, but the ratio $(\frac{V_{av}}{V_c})$ for a longer capsule is lower when $R_v > 1.0$ and is higher when $R_v < 1.0$ than that for the shorter ones of the same K and material, (cf section (6.1.1.2)).

Both Figures 6.35 and 6.36 also show the effects of K on P. In general P decreases as K is increased. The reasons for this are obvious if we refer to Equation (6.18). As K increases, the slight increase in $(\Delta P/L)_c$ is offset by a decrease in $(\frac{V_{av}}{V_c})$ and (D/d) itself. Thus the energy requirements per unit capsule discharge may be minimized by transporting a capsule of nearly the same diameter as the pipeline. Practically, of course, physical considerations such as the maneuverability of the capsule through the bends in the pipeline will limit the capsule diameter.

As may be expected a heavier capsule requires more P than the lighter ones, since $(\Delta P/L)_c$ increases as the capsule weight increases.

To conclude this section the effects of the various variables on P may be summarized as: when $R_v < 1.0$, P decreases with increasing V_{av} and increases with L/d ratio; when $R_v > 1.0$, P increases with V_{av} and decreases with increasing L/d; and the effect of increasing K is always to decrease P at any V_{av}.

CHAPTER 7

CONCLUSIONS

On the basis of the analyses and the experimental results presented in this thesis, the following conclusions can be made:

(1) For both of the cylindrical and spherical capsules hydrodynamically driven in a vertical pipeline:

(a) The velocity ratio R_v is dependent upon four independent variables: V_{av} (or Re_D), L/d, K and (S_c-1);

(b) R_v increases as V_{av} increases and the rate of increase in R_v is large at low V_{av} but is small at high V_{av}'s. Only nylon capsules (S_c = 1.15) were observed to reach the state of R_v > 1.0. Also when R_v>1.0, R_v tends to become constant, hence increasing V_{av} in this velocity range has virtually no effect on R_v.

(c) The effect of K on R_v is to increase R_v for a given capsule of constant L/d and σ at a fixed V_{av}. But when R_v > 1.0, the smaller K capsules tend to have a higher V_c than the larger K ones of the same L/d and σ. This phenomenor is more pronounced for spheres than for cylinders with blunt ends, and therefore suggests the effect of the capsule end configuration on R_v and the possible increase of R_v for smaller K capsules by using capsules with streamlined noses, at high V_{av}'s.

(d) An increase of (S_c-1) for a capsule of constant K and L/d always decreases the R_v ratio at a decreasing rate with increasing V_{av}.

(e) The steady-state V_c at any given V_{av} can be predicted by the following semi-empirical formulas:

For cylinders:

$$V_c = \frac{1}{K^{0.128}}\left[V_{av}(L/d)^{0.128} - \sqrt{2gD(S_c-1)(L/d)}\,(1-K^2)(1-\frac{1}{S_c})^{0.05}\right] \qquad (6.5)$$

For spheres:

$$V_c = \frac{1}{K^{0.34}}\left[V_{av}-\sqrt{\tfrac{4}{3}gD(S_c-1)/K}(1-K^2)(1-\frac{1}{S_c})^{0.05}\right] \qquad (6.9)$$

Both of which are found to be especially good for the median and high R_v ranges.

(f) The pressure gradient ratio R_p, is a function of four independent variables: V_{av} (or Re_D), K, L/d and (S_c-1). The effects of these four variables on R_p are: R_p decreases with an increase in V_{av}, but increases with increasing K and (S_c-1), and there is essentially no effect of L/d on R_p.

(2) For the cylindrical capsules:

(a) For a cylinder of the same σ and K at a constant V_{av}, R_v decreases with increase in L/d when $R_v < 1.0$, but increases with increase in L/d when $R_v > 1.0$. The effect of varying L/d on R_v decreases as V_{av} is increased. Furthermore due to the fact that the spheres have in effect a L/d = 1.0 and therefore are the shortest capsules that were studied, the spheres have a higher R_v than the cylinders of the same K and σ when $R_v \lessgtr 1.0$, and a lower value when $R_v > 1.0$.

(b) The total pressure gradient $(\Delta P/L)_c$ associated with a cylinder can be expressed by the equation of

$$(\Delta P/L)_c = (\Delta P_o/L) + (\Delta P/L)_L$$

The component $(\Delta P_o/L)$, which is the increase of the pressure gradient due to the presence of the capsule, can be predicted by the following semi-empirical formula

$$(\Delta P_o/L) = 1.15(k)^{1.84} (\sigma-\rho)g \qquad (6.13)$$

The component $(\Delta P/L)_L$, which is the free pipe pressure gradient due to the fluid alone, can be calculated by the Darcy-Weisbach equation

$$(\Delta P/L)_L = f \frac{\rho V_{av}^2}{D} \qquad (6.14)$$

where f can be determined by using standard procedures for pipe flow.

$(\Delta P/L)_c$ for a given cylinder at any V_{av} can be predicted by means of Equations (6.13) and (6.14) with a precision of better than $\pm 5\%$.

(d) The unit energy requirements based on the mass flow rate of a cylinder, P, is a function of four independent variables, and their individual effects on P are: When $R_v < 1.0$ P decreases with increasing V_{av} and increases with increasing L/d; When $R_v > 1.0$ P increases with increasing V_{av} and decreases with increasing L/d; and the effect of increasing K or decreasing σ is always to decrease P at any V_{av}.

(3) Finally, in order to obtain universal correlations of the flow of capsule in a vertical pipeline, it is apparent that there is a need for more research on spherical and irregular geometry capsules as well as on the effects of the physical properties of the carrier fluid.

APPENDIX A

ERROR ANALYSIS

Listed in Table (A-1) are the estimates of relative uncertainty of the primary measurements made in the present work. They include factors such as instrument error, calibration error, reading error and manufacture's quotations etc.

By using the "most probable" method, the relative error of each of the important variables used in this study are determined as follows:

(1) Error in V_{av}

For a given variable M, which is a function of x, y..., the relative error in M may be expressed by the equation

$$\frac{dM}{M} = \{\frac{1}{M^2}[(\frac{\delta M}{\delta x} dx)^2 + (\frac{\delta M}{\delta y} dy)^2 + ...]\}^{1/2}$$

or $E_M = [(Ex)^2 + (Ey)^2 + ...]^{1/2}$ (A-1)

where Ex, Ey ... are the relative uncertainty in x, y,...

Since V_{av} is calculated from

$$V_{av} = \frac{4Q}{\pi D^2} = \frac{CQ}{D^2}$$ where Q is the flowrate

$$\therefore \frac{dM}{M} = \{(\frac{dQ}{Q})^2 + (2\frac{dD}{D})^2\}^{1/2}$$

Hence, from Table (A-1), the relative error in V_{av} is

$$E_{V_{av}} = [(E_Q)^2+(2E_D)^2]^{1/2} = [4^2+(2x1)^2]^{1/2} \cong \pm 4.5\%$$

TABLE (A-1)

Uncertainty estimates in the measured primary quantities.

DESCRIPTION	SYMBOL	UNCERTAINTY ± %
Pipe inside diameter	D	1.0
Capsule diameter	d	1.0
Length between pressure taps	L_t	1.0
Length between PL units	L_p	1.0
Length of capsules	L_c	1.0
Flow rate measurement	Q	4.0
Pressure drop measurements	ΔP_o	6.0
	ΔP_L	4.0
Capsule passage time measurement	t	3.0
Capsule density	σ	1.0
Water temperature	T	6.0

(2) Error in V_c

Since $V_c = L_p/t$

∴ The relative error in V_c is

$$E_{V_c} = [(E_{L_p})^2 + (E_t)^2]^{1/2} = [(0.5)^2+(3)^2]^{1/2} \approx \pm 3.0\%$$

(3) Error in R_v

Since $R_v = \frac{V_c}{V_{av}}$

∴ The relative error in R_v is

$$E_{RV} = [(E_{V_c})^2 + (E_{V_{av}})^2]^{1/2} = [(3)^2+(4.5)^2]^{1/2} \cong \pm 5.4\%$$

(4) Error in $(\Delta P_o/L)$

Since $(\Delta P_o/L) = \frac{P_o}{L_c}$

$$\therefore E(\Delta P_o/L) = [(E_{\Delta P_o})^2+(E_{L_c})^2]^{1/2} = [6^2+1]^{1/2} \cong \pm 6.1\%$$

(5) Error in $(\Delta P/L)_L$

Since $(\Delta P/L)_L = \frac{\Delta P_L}{L_t}$

$$\therefore E(\Delta P/L)_L = [(E_{\Delta P_L})^2 + (E_{L_t})^2]^{1/2} = [(4)^2+1]^{1/2} \cong \pm 4.1\%$$

(6) Error in $(\Delta P/L)_c$

Since $(\Delta P/L)_c = (\Delta P_o/L) + (\Delta P/L)_L$

The relative error in $(\Delta P/L)_c$ is

$$E_{(\Delta P/L)_c} = \frac{d(\Delta P/L)_c}{(\Delta P/L)_c} = \{[\frac{d(\Delta P_o/L)}{(\Delta P/L)_c}]^2 + [\frac{d(\Delta P/L)_L}{(\Delta P/L)_L}]^2\}^{1/2}$$

Since the uncertainty in ΔP_o is larger than that in P_L, it is expected that the maximum relative error in $(\Delta P/L)_c$ would occur at a capsule for which $(\Delta P_o/L)$ is the maximum and $(\Delta P/L)_L$ is the minimum. The capsule which is under such condition is an aluminum cylinder of K = .815 and L/d = 4 at V_{av} = 1.074 m/s. For this capsule the pressure components are: $(\Delta P_o/L)$ = 13.027 and $(\Delta P/L)_L$=0.1604 KPa.

Hence the maximum relative error in $(\Delta P/L)_c$ is:

$$E(\Delta P/L)_c = \{[\frac{0.06x13.027}{13.187}]^2 + [\frac{0.04x0.1604}{13.187}]^2\}^{1/2} \times 100 \cong \pm 5.9\%$$

(7) Error in K and L/d

Since K = d/D and L/d = $\frac{L_d}{d}$

$$\therefore E_{(K)} = [(E_d)^2 + (E_D)^2]^{1/2} = (1+1)^{1/2} \cong \pm 1.4\%$$

and
$$E_{(L/d)} = [(E_L)^2 + (E_d)^2]^{1/2} = (1+1)^{1/2} \cong \pm 1.4\%$$

APPENDIX B

CALIBRATION CURVES

(B-1). Calibration of Flowmeter

There were two flow-sensors used for the measurement of the water flowrate in the pipeline. The one located in the 5 cm by-pass loop is good for the range of 0-12 litres/s, (0-180 USGPM) and the other one located in the main line is good for 12-30 litres/s (180-500 USGPM).

Prior to the experiment, these two flow sensors were calibrated by comparing the indicated GPM by the readout device to those obtained by the pitot-tube measurement.

The results are listed in Table (B-1) and the calibration curves are presented in Figures (B-1) and (B-2). These curves show excellent agreement between the indicated and the calculated (true) GPM.

Since the flowrate measurements were recorded by a recorder, a calibration curve with indicated GPM against voltage output from the recorder was needed. Figure (B-3) shows such a curve, and the data of which are listed in Table (B-2).

The two equations, established from the data on Figure (B-3), which represent the two calibration curves of the flowmeters were used for the calculation of the flowrates throughout the experiments.

Table (B-1)

Calibration data for MK 315 flowsensors

FLO-SENSOR #1 (By-pass loop)			FLO -SENSOR #2 (main line)		
INDICATED GPM	MANOMETER READING Δh(cm)	CALCULATED* GPM	INDICATED GPM	MANOMETER READING Δh(cm)	CALCULATED* GPM
47	0.25	48	148	2.2	143
59	0.4	61	163	2.7	158
97	1.0	96	176	3.2	172
122	1.6	122	181	3.5	180
142	2.2	143	193	4.1	195
159	2.7	158	224	5.4	224
174	3.2	172	278	8.4	279
184	3.5	180	305	10.2	308
201	4.1	195	329	11.8	331
			367	14.7	369
			385	15.9	384
			423	19.5	425
			430	19.6	426

* Calculated GPM = 96.284 $\sqrt{\Delta h(cm)}$

Table (B-2)

Calibration data for flowsensor with recorder

FLO-SENSOR #1		FLO-SENSOR #2	
VOLTS	CORRESPONDING USGPM	VOLTS	CORRESPONDING USGPM
0.40	36	2.05	182
0.63	58	2.98	257
0.88	84	3.15	272
1.18	108	3.50	300
1.46	129	3.70	321
1.82	160	3.90	333
2.05	186	4.20	359
		4.60	393
		4.87	409

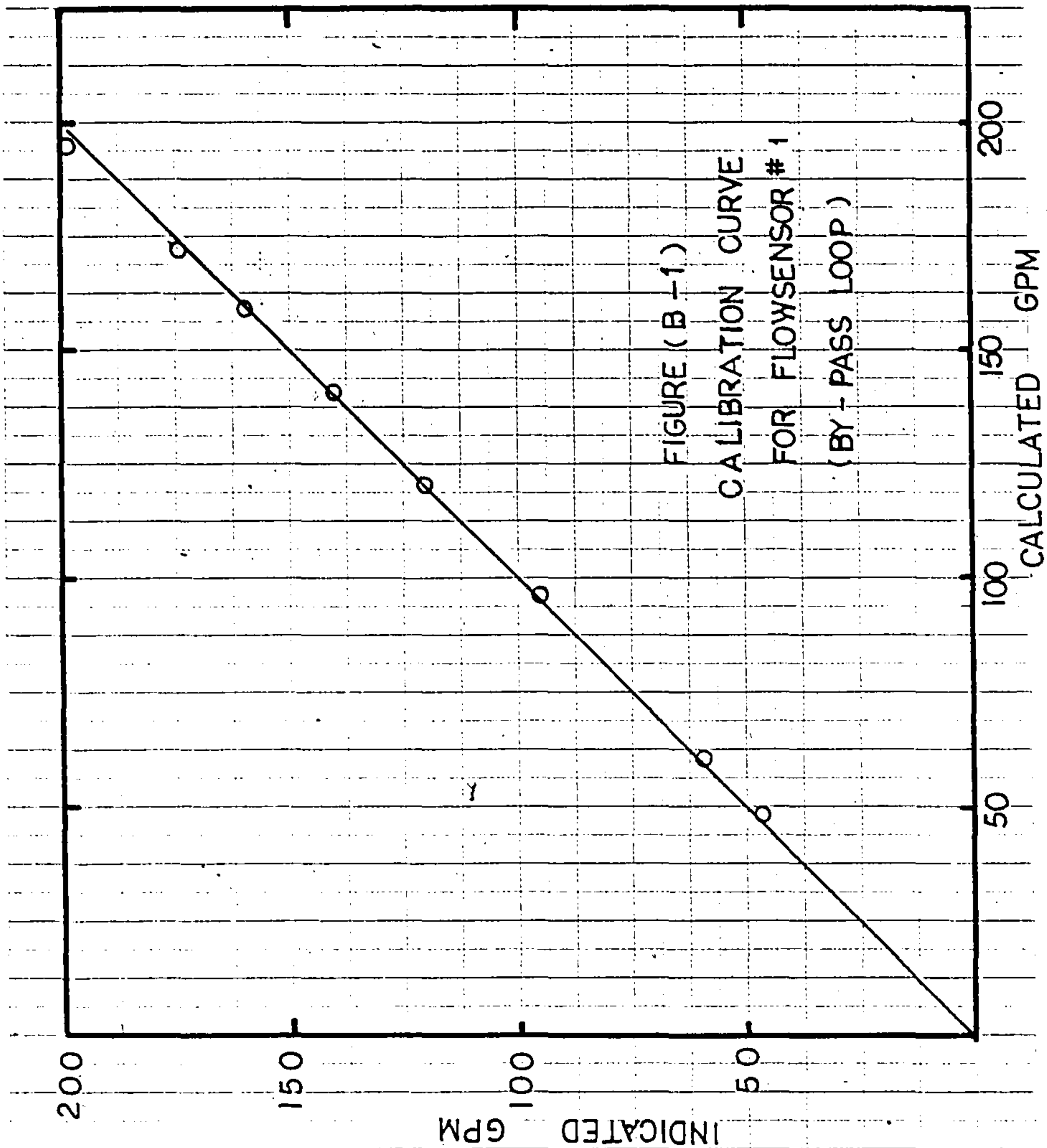


FIGURE (B – 1)
CALIBRATION CURVE
FOR FLOWSENSOR # 1
(BY - PASS LOOP)

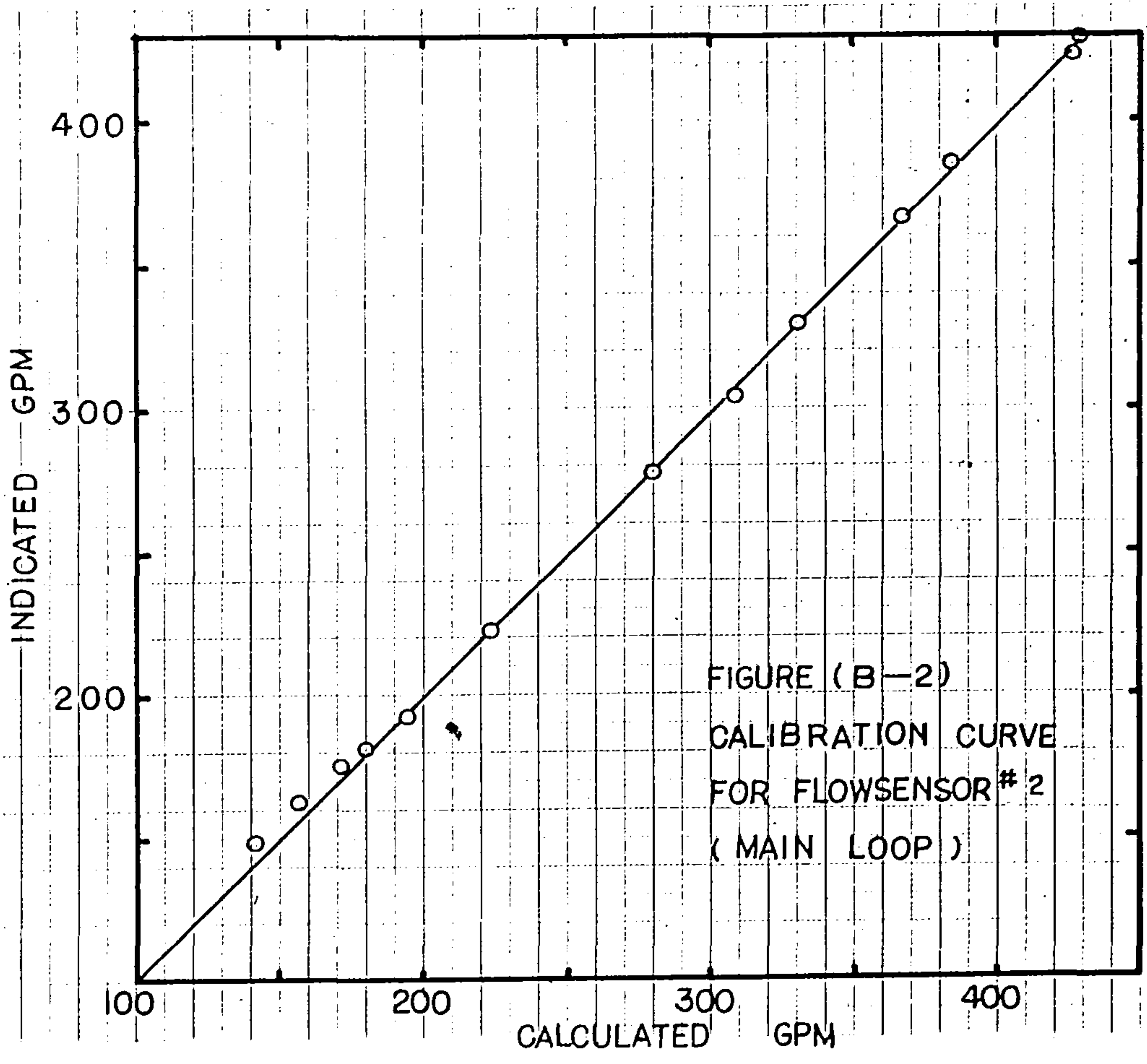


FIGURE (B—2)
CALIBRATION CURVE
FOR FLOWSENSOR # 2
(MAIN LOOP)

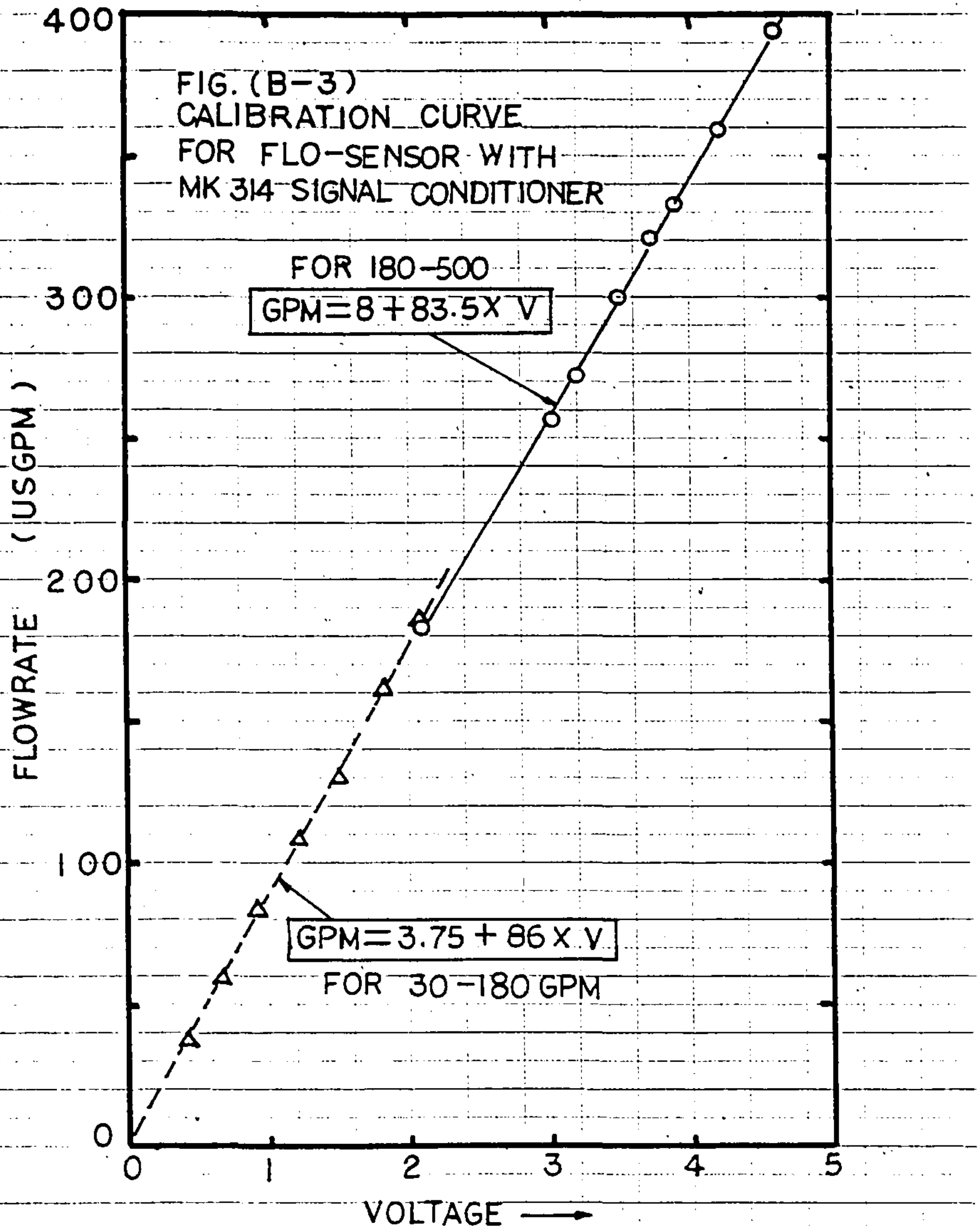
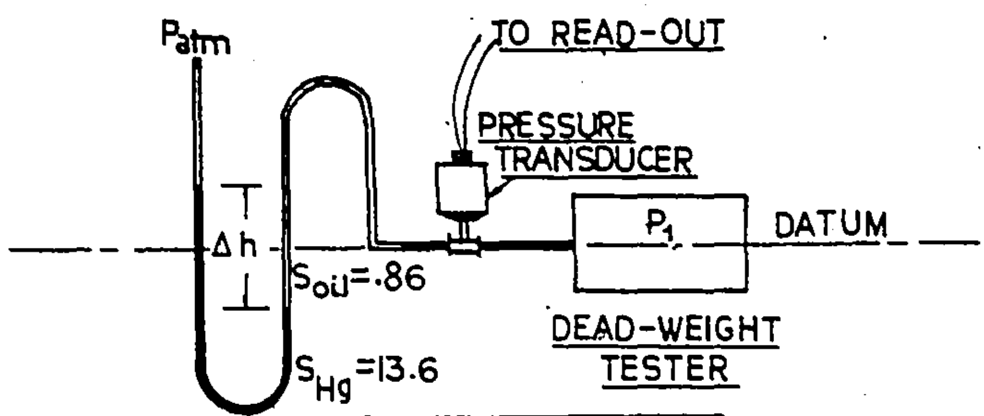


FIG. (B-3)
CALIBRATION CURVE
FOR FLO-SENSOR WITH
MK 314 SIGNAL CONDITIONER
FOR 180-500
GPM=8+83.5X V
GPM=3.75+86 X V
FOR 30-180 GPM
400
300
200
100
0
FLOWRATE (USGPM)
0
1
2
3
4
5
VOLTAGE

(B-2) Calibration of Pressure Transducer

The calibration of the pressure transducer with a ± 5 psiD diaphram was done using a dead-weight tester with a set-up as shown in Figure (B-4).



$$\Delta P = P_1 - P_{atm} = (\gamma_{Hg} - \tfrac{1}{2}\gamma_{oil})\Delta h \quad (B-1)$$

FIG.(B.4): CALIBRATION OF PRESS. TRANSDUCER

By varying the pressure inside the tester, a corresponding variation of the manometer fluid column and a direct pressure reading from the pressure transducer were obtained. The true pressures calculated from Equation (B-1) were plotted against the transducer reading to obtain the calibration curve of the transducer with the particular diaphram (Figure (B-5)).

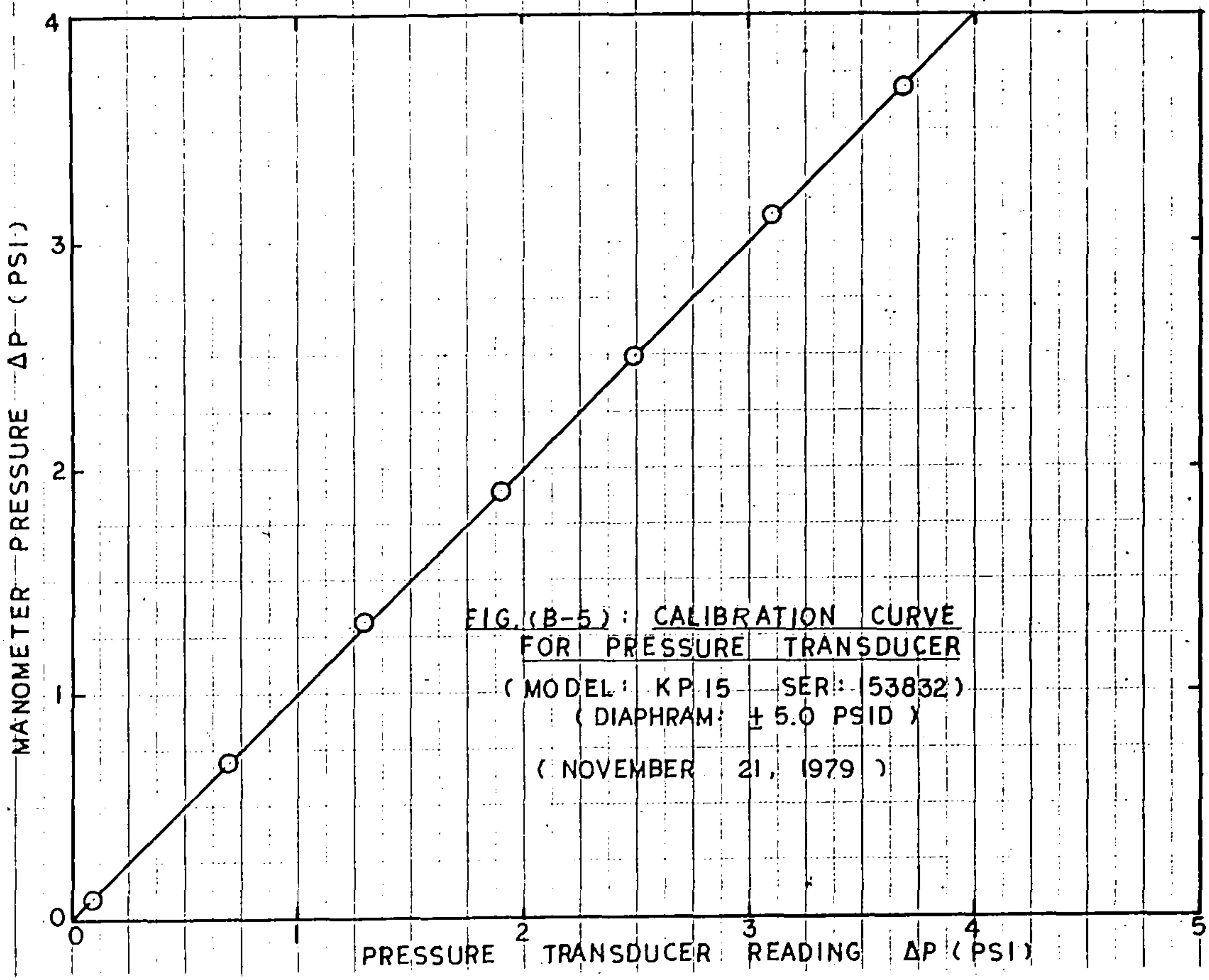


FIG. (B-5): CALIBRATION CURVE FOR PRESSURE TRANSDUCER
(MODEL: KP 15 SER: 53832)
(DIAPHRAM: ± 5.0 PSID)
(NOVEMBER 21, 1979)

APPENDIX C

The Velocity Profile of the Test Section

One important condition under which the experiments were performed was that the free pipe flow in the test section must be fully developed and symmetric. In order to confirm this, the free pipe flow velocity profiles at the "pL" unit stations #6 and #19 along the test section were determined by using the pitot-tube traverse method.

The measured results are listed in Table (C-1) and the velocity profiles are shown in Figure (C-1).

Table (C-1)

Cross-sectional Velocity Distribution of the Test Section

STATION #6				STATION #19			
r/R	Pitot-tube Measurement (cm)	u (m/s)	$\frac{u}{u_{max}}$	r/R	Pitot-tube Measurement (cm)	u (m/s)	$\frac{u}{u_{max}}$
.83	6.7	4.072	.81	.83	7	4.16	.84
.67	8.3	4.53	.91	.67	7.8	4.39	.88
.50	8.9	4.69	.94	.50	9	4.72	.95
.33	9.3	4.80	.96	.33	9.5	4.85	.97
.17	9.7	4.90	.98	.17	9.8	4.92	.99
0	10.1	5.00	1.00	0	10.0	4.97	1.00
-.17	9.9	4.95	.99	-.17	9.9	4.95	.99
-.33	9.5	4.85	.97	-.33	9.2	4.77	.96
-.50	9.2	4.77	.95	-.50	8.9	4.69	.94
-.67	8.6	4.61	.92	-.67	7.8	4.39	.88
-.83	7.2	4.22	.84	-.83	6.8	4.10	.82

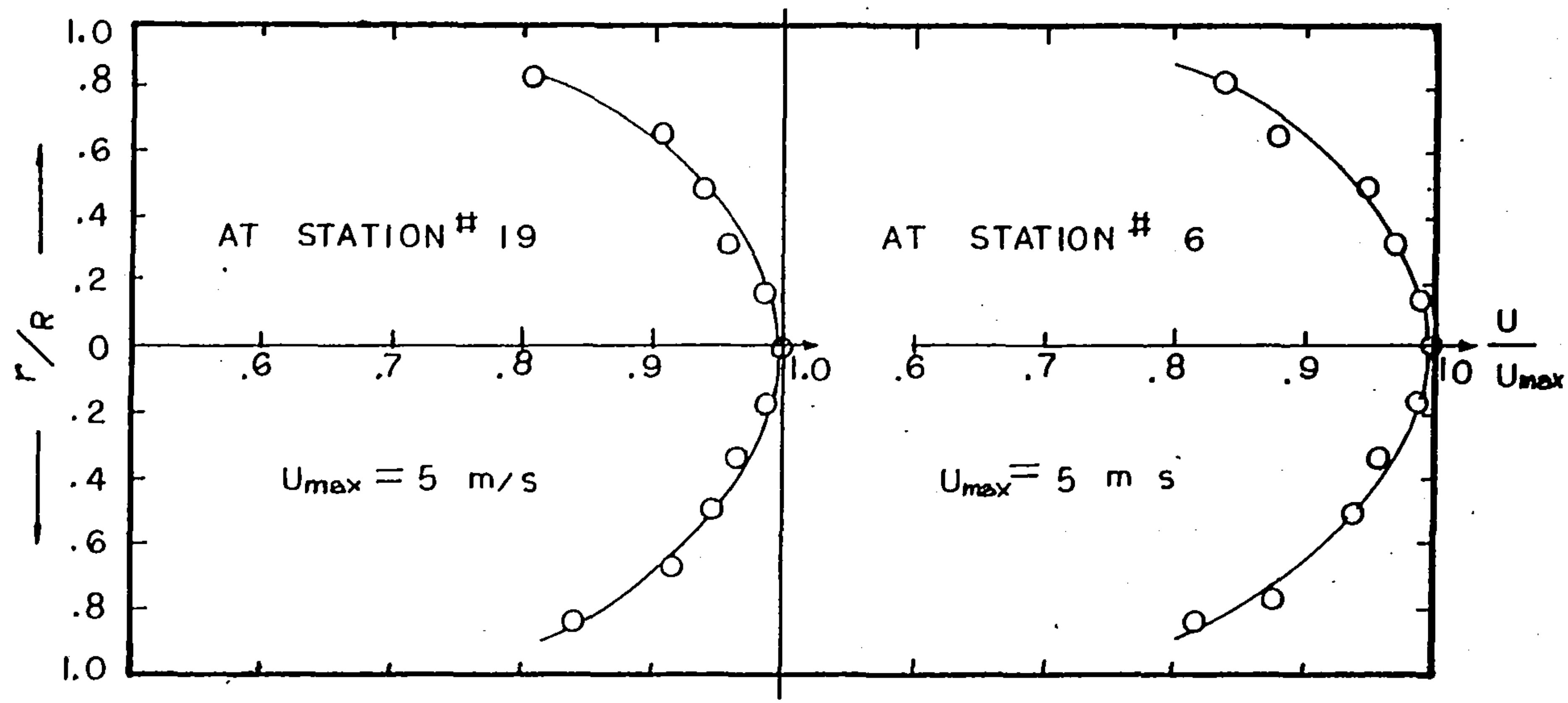


FIGURE (C-1) : THE VELOCITY PROFILE IN THE TEST SECTION

APPENDIX D

DATA TABLES

LIST OF TABLES

(D. 1) EXPERIMENTAL DATA - NYLON CYLINDERS

K= .489 S= 1.15

VAV	VC	RV	DPO	DPL	(DPO/L)	(DP/L)L	RE(D)
(M/S)	(M/S)	(-)	(KPA)	(KPA)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)							
1.058	.769	.7268	.0689	.4138	.4523	.1481	73700
1.728	1.636	.9468	.0689	.9662	.4523	.3458	120300
2.403	2.51	1.0445	.0689	1.8273	.4523	.654	167400
3.006	3.34	1.1111	.0689	2.758	.4523	.9871	209400
3.696	4.196	1.1353	.0689	4.0681	.4523	1.456	257400
4.386	5.03	1.1468	.0689	5.7221	.4523	2.048	305500
5.077	5.892	1.1605	.0689	7.5857	.4523	2.715	353600
(L/D= 7)							
1.045	.605	.5789	.131	.4345	.4911	.1555	72800
1.722	1.454	.8444	.131	.9653	.4911	.3455	119900
2.37	2.4	1.0127	.131	1.7926	.4911	.6416	165100
2.95	3.234	1.0963	.131	2.5512	.4911	.9131	205500
3.696	4.23	1.1445	.131	4.1379	.4911	1.481	257400
4.303	5.063	1.1766	.131	5.7277	.4911	2.05	299700
4.988	5.919	1.1866	.131	7.5857	.4911	2.715	347400
(L/D= 10)							
1.098	.519	.4727	.1723	.4138	.4523	.1481	76500
1.711	1.407	.8223	.1723	.9307	.4523	.3331	119200
2.371	2.366	.9979	.1723	1.7583	.4523	.6293	165100
3.033	3.347	1.1035	.1723	2.6889	.4523	.9624	211200
3.696	4.29	1.1607	.1723	4.0681	.4523	1.456	257400
4.386	5.288	1.2057	.1723	5.1717	.4523	1.851	305500
5.02	6.232	1.2414	.1723	7.2923	.4523	2.61	349600
(L/D= 14)							
1.098	.347	.316	.224	.4599	.42	.1646	76500
1.728	1.316	.7616	.224	.9771	.42	.3497	120300
2.371	2.34	.9869	.224	1.7815	.42	.6376	165100
3.006	3.33	1.1078	.224	2.9086	.42	1.041	209400
3.694	4.325	1.1708	.224	4.1379	.42	1.481	257300
4.414	5.439	1.2322	.224	5.9764	.42	2.139	307400
5.022	6.363	1.267	.224	7.8159	.42	2.7974	349800

DPO & (DPO/L): PRESSURE DROP & PRESSURE GRADIENT DUE TO CAPSULE
DPL & (DP/L)L: PRESSURE DROP & PRESSURE GRADIENT DUE TO WATER
RE(D): FREE PIPE REYNOLDS NO. M=METER S=SECOND PA=PASCAL

(D. 2) EXPERIMENTAL DATA - NYLON CYLINDERS

K= .652 S= 1.15

VAV	VC	RV	DPO	DPL	(DPO/L)	(DP/L)L	RE(D)
(M/S)	(M/S)	(-)	(KPA)	(KPA)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)							
.619	.345	.5574	.1585	.1724	.7803	.0617	43100
1.074	.824	.7672	.1585	.4688	.7803	.1678	74800
1.733	1.694	.9775	.1585	1.0343	.7803	.3702	120700
2.315	2.502	1.0808	.1585	1.7926	.7803	.6416	161200
3.066	3.424	1.1168	.1654	2.9644	.8142	1.061	213500
3.696	4.252	1.1504	.1654	4.2748	.8142	1.53	257400
4.392	5.136	1.1694	.1654	5.5154	.8142	1.974	305900
5.076	5.995	1.181	.1654	7.5857	.8142	2.715	353500
(L/D= 7)							
.676	.243	.3595	.2757	.1724	.7754	.0617	47100
1.045	.729	.6976	.2757	.4138	.7754	.1481	72800
1.768	1.654	.9355	.2757	1.0894	.7754	.3899	123100
2.371	2.49	1.0502	.2757	1.7926	.7754	.6416	165100
3.006	3.385	1.1261	.2964	2.8946	.8336	1.036	209400
3.641	4.22	1.159	.2964	4.0681	.8336	1.456	253600
4.331	5.16	1.1914	.2964	5.1717	.8336	1.851	301600
(L/D= 10)							
1.045	.664	.6354	.3791	.3791	.7464	.1357	72800
1.733	1.603	.925	.3791	.9653	.7464	.3455	120700
2.427	2.53	1.0424	.3791	1.7236	.7464	.6169	169000
3.033	3.412	1.125	.3791	2.6199	.7464	.9377	211200
3.706	4.36	1.1765	.3929	3.9982	.7735	1.431	258100
4.386	5.34	1.2175	.3929	5.3785	.7735	1.925	305500
(L/D= 14)							
1.074	.587	.5466	.5169	.5172	.727	.1851	74800
1.711	1.52	.8884	.5169	1.0919	.727	.3908	119200
2.37	2.466	1.0405	.5169	1.7242	.727	.6171	165100
3.054	3.458	1.1323	.5169	2.875	.727	1.029	212700
3.752	4.453	1.1868	.5169	4.0234	.727	1.44	261300
4.362	5.401	1.2382	.5514	5.8618	.7754	2.098	303800

DPO & (DPO/L): PRESSURE DROP & PRESSURE GRADIENT DUE TO CAPSULE
DPL & (DP/L)L: PRESSURE DROP & PRESSURE GRADIENT DUE TO WATER
RE(D): PREE PIPE REYNOLDS NO. M=METER S=SECOND PA=PASCAL

(D. 3) EXPERIMENTAL DATA - NYLON CYLINDERS

K= .815 S= 1.15

VAV	VC	RV	DPO	DPL	(DPO/L)	(DP/L)L	RE(D)
(M/S)	(M/S)	(-)	(KPA)	(KPA)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)							
.397	.208	.5239	.2931	.0861	1.154	.0308	27600
.661	.522	.7897	.2931	.2414	1.154	.0864	46000
1.045	.994	.9512	.2931	.4482	1.154	.1604	72800
1.711	1.761	1.0292	.2931	.9824	1.154	.3516	119200
2.453	2.685	1.0946	.2931	1.9857	1.154	.7107	170800
3.143	3.527	1.1222	.2931	3.0343	1.154	1.086	218900
3.834	4.433	1.1562	.3101	4.3447	1.221	1.555	267000
(L/D= 7)							
.419	.16	.3819	.5169	.0897	1.163	.0321	29200
.675	.472	.6993	.5169	.1724	1.163	.0617	47000
1.044	.954	.9138	.5169	.4482	1.163	.1604	72700
1.651	1.702	1.0309	.5031	.9307	1.132	.3331	115000
2.392	2.613	1.0924	.5031	1.7926	1.132	.6416	166600
3.143	3.664	1.1658	.5169	3.0008	1.163	1.074	218900
3.806	4.492	1.1802	.5169	4.4816	1.163	1.604	265100
(L/D= 10)							
.662	.45	.6801	.7238	.1931	1.14	.0691	46100
1.039	.903	.8691	.7238	.3998	1.14	.1431	72400
1.688	1.796	1.064	.7238	.879	1.14	.3146	117600
2.508	2.853	1.1376	.6901	1.7937	1.087	.642	174700
3.171	3.777	1.1911	.7409	2.8946	1.167	1.036	220800
3.861	4.793	1.2414	.7409	4.4117	1.167	1.579	268900
(L/D= 14)							
.661	.407	.6154	.9991	.1724	1.124	.0617	46100
1.039	.89	.8566	.9991	.3736	1.124	.1337	72400
1.668	1.781	1.0677	.9653	.9195	1.086	.3291	116200
2.508	2.853	1.1376	.9306	1.8966	1.047	.6788	174700
3.171	3.829	1.2075	.9653	3.1041	1.086	1.111	220800
3.972	4.98	1.2538	1.0337	5.0599	1.163	1.811	276600

DPO & (DPO/L): PRESSURE DROP & PRESSURE GRADIENT DUE TO CAPSULE
DPL & (DP/L)L: PRESSURE DROP & PRESSURE GRADIENT DUE TO WATER
RE(D): FREE PIPE REYNOLDS NO. M=METER S=SECOND PA=PASCAL

(D.4) EXPERIMENTAL DATA - ALUMINUM CYLINDERS

K= .489 S= 2.7

VAV	VC	RV	DPO	DPL	(DPO/L)	(DP/L)L	RE(D)
(M/S)	(M/S)	(-)	(KPA)	(KPA)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)							
2.381	.471	.1978	.7926	1.7915	5.202	.6412	165800
3.054	1.282	.4198	.7926	2.8946	5.202	1.036	212700
3.696	2.102	.5687	.7926	4.0681	5.202	1.456	257400
4.362	3.135	.7187	.7926	5.5154	5.202	1.974	303800
5.078	4.108	.809	.7926	7.446	5.202	2.665	353700
(L/D= 7)							
2.778	.447	.1609	1.3095	2.3377	4.911	.8367	193500
3.042	.796	.2617	1.3442	2.9309	5.041	1.049	211900
3.347	1.171	.3499	1.3783	3.7915	5.169	1.357	233100
3.704	1.664	.4492	1.3783	4.2748	5.169	1.53	258000
4.258	2.451	.5756	1.3783	5.5601	5.169	1.99	296600
4.696	3.087	.6574	1.3783	6.7559	5.169	2.418	327100
(L/D= 10)							
2.978	.199	.0668	1.8955	2.8275	4.976	1.012	207400
3.641	1.156	.3175	1.8955	3.9312	4.976	1.407	253600
4.331	2.238	.5167	1.8955	5.1717	4.976	1.851	301600
4.994	3.129	.6266	1.8955	7.7925	4.976	2.789	347800
(L/D= 14)							
3.696	.723	.1956	2.5849	4.1379	4.847	1.481	257400
4.331	1.702	.393	2.5849	6.035	4.847	2.16	301600
5.022	2.744	.5464	2.5849	7.1834	4.847	2.571	349800

DPO & (DPO/L): PRESSURE DROP & PRESSURE GRADIENT DUE TO CAPSULE
DPL & (DP/L)L: PRESSURE DROP & PRESSURE GPADIENT DUE TO WATER
RE(D): PREE PIPE REYNOLDS N0. M=METER S=SECOND PA=PASCAL

(D.5) EXPERIMENTAL DATA - ALUMINUM CYLINDERS

K= .652 S= 2.7

VAV	VC	RV	DPO	DPL	(DPO/L)	(DP/L)L	RE(D)
(M/S)	(M/S)	(-)	(KPA)	(KPA)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)							
1.756	.335	.1908	1.8264	.9653	8.99	.3455	122300
2.343	1.076	.4592	1.8264	1.7239	8.99	.617	163200
3.06	2.003	.6546	1.8264	2.5856	8.99	.9254	213100
3.729	2.852	.7648	1.8264	4.1379	8.99	1.481	259700
4.436	3.773	.8505	1.861	5.6886	9.16	2.036	308900
5.098	4.626	.9074	1.861	8.0998	9.16	2.899	355100
(L/D= 7)							
2.183	.269	.1232	3.1707	1.4836	8.918	.531	152000
2.47	.623	.2522	3.1707	1.9307	8.918	.691	172000
2.729	.983	.3602	3.1707	2.3442	8.918	.839	190100
2.922	1.426	.488	3.1707	2.7577	8.918	.987	203500
3.42	2.025	.5921	3.1707	3.5847	8.918	1.283	238200
3.74	2.498	.6679	3.2393	4.3447	9.111	1.555	260500
4.358	3.281	.7529	3.2393	6.0909	9.111	2.18	303500
(L/D= 10)							
2.37	.405	.1709	4.5488	1.7239	8.956	.617	165100
3.033	1.334	.4398	4.5488	2.8946	8.956	1.036	211200
3.673	2.252	.6131	4.5488	4.1379	8.956	1.481	255800
4.359	3.249	.7454	4.5488	5.6886	8.956	2.036	303600
5.076	4.211	.8296	4.5488	7.7226	8.956	2.764	353500
(L/D= 14)							
3.033	.943	.3109	6.3755	2.875	8.966	1.029	211200
3.696	1.932	.5227	6.4103	4.3111	9.015	1.543	257400
4.414	2.968	.6724	6.5475	6.035	9.208	2.16	307400
5.054	4.021	.7956	6.5475	8.0467	9.208	2.88	352000

DPO & (DPO/L): PRESSURE DROP & PRESSURE GRADIENT DUE TO CAPSULE
DPL & (DP/L)L: PRESSURE DROP & PRESSURE GRADIENT DUE TO WATER
RE(D): PREE PIPE REYNOLDS N0. M=METER S=SECOND PA=PASCAL

(D. 6) EXPERIMENTAL DATA - ALUMINUM CYLINDERS

K= .815 S= 2.7

VAV	VC	RV	DPO	DPL	(DPO/L)	(DP/L)L	RE(D)
(M/S)	(M/S)	(-)	(KPA)	(KPA)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)							
1.074	.256	.2384	3.3083	.4482	13.027	.1604	74800
1.699	.986	.5803	3.3083	1.1031	13.027	.3948	118300
2.458	1.812	.7372	3.274	1.8273	12.892	.654	171200
3.116	2.73	.8761	3.274	3.0343	12.892	1.086	217000
3.861	3.716	.9624	3.274	4.4816	12.892	1.604	268900
(L/D= 7)							
1.33	.392	.2947	5.6863	.5515	12.795	.1974	92600
1.643	.701	.4267	5.6863	.8619	12.795	.3085	114400
2.012	1.161	.577	5.6863	1.3101	12.795	.4689	140100
2.481	1.783	.7187	5.6863	1.896	12.795	.6786	172800
2.779	2.163	.7783	5.6863	2.4132	12.795	.8637	193500
3.309	2.888	.8728	5.7206	3.3444	12.872	1.197	230500
(L/D= 10)							
1.756	.714	.4066	8.2706	.9997	13.027	.3578	122300
2.453	1.623	.6616	8.2706	1.896	13.027	.6786	170800
3.171	2.592	.8174	8.2706	2.9644	13.027	1.061	220800
3.972	3.745	.9428	8.2706	4.7582	13.027	1.703	276600
(L/D= 14)							
1.728	.602	.3484	11.5451	1.0343	12.989	.3702	120300
2.503	1.524	.6089	11.5451	1.9541	12.989	.6994	174300
3.171	2.527	.7969	11.5451	3.1041	12.989	1.111	220800
4.049	3.811	.9412	11.7167	5.3449	13.182	1.913	282000
4.524	4.511	.9971	11.5451	6.4374	12.989	2.304	315100

DPO & (DPO/L): PRESSURE DROP & PRESSURE GRADIENT DUE TO CAPSULE
DPL & (DP/L)L: PRESSURE DROP & PRESSURE GPADIENT DUE TO WATER
RE(D): PREE PIPE REYNOLDS N0. M=METER S=SECOND PA=PASCAL

(D.7) PREDICTION OF VC (EQN.6.5)- NYLON CYLINDERS

K= .489 S= 1.15

VAV	VC	RV	VC1	RV1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(L/D= 4)						
1.058	.769	.7268	.6634	.627	.1592	73700
1.728	1.636	.9468	1.5402	.8913	.0622	120300
2.403	2.505	1.0424	2.4235	1.0085	.0336	167400
3.006	3.34	1.1111	3.2127	1.0688	.0396	209400
3.696	4.196	1.1353	4.1157	1.1135	.0195	257400
4.386	5.033	1.1475	5.0186	1.1442	2.9E-03	305500
5.077	5.892	1.1605	5.9229	1.1666	-5.2E-03	353600
(L/D= 7)						
1.045	.605	.5789	.5151	.4929	.1746	72800
1.722	1.454	.8444	1.4668	.8518	-8.7E-03	119900
2.37	2.4	1.0127	2.3778	1.0033	9.3E-03	165100
2.95	3.234	1.0963	3.1932	1.0824	.0128	205500
3.696	4.23	1.1445	4.242	1.1477	-2.8E-03	257400
4.303	5.063	1.1766	5.0953	1.1841	-6.3E-03	299700
4.988	5.919	1.1866	6.0583	1.2146	-.023	347400
(L/D= 10)						
1.098	.519	.4727	.4754	.433	.0917	76500
1.711	1.407	.8223	1.3775	.8051	.0214	119200
2.37	2.366	.9983	2.3472	.9904	8E-03	165100
3.033	3.347	1.1035	3.3228	1.0956	7.3E-03	211200
3.696	4.286	1.1596	4.2984	1.163	-2.9E-03	257400
4.386	5.288	1.2057	5.3138	1.2115	-4.9E-03	305500
5.022	6.232	1.2409	6.2497	1.2445	-2.8E-03	349800
(L/D= 14)						
1.098	.347	.316	.3376	.3075	.0279	76500
1.728	1.316	.7616	1.3055	.7555	8.1E-03	120300
2.37	2.34	.9873	2.2918	.967	.0211	165100
3.01	3.33	1.1063	3.275	1.088	.0168	209600
3.694	4.325	1.1708	4.3258	1.171	-2E-04	257300
4.414	5.439	1.2322	5.4319	1.2306	1.3E-03	307400
5.022	6.363	1.267	6.366	1.2676	-5E-04	349800

VC & RV: EXPERIMENTAL VC1 & RV1: EMPERICAL(EQUATION(6.5))
RE(D): FREE PIPE REYNOLDS NUMBER E:DEVIATION OF VC1 FROM VC

(D.8) PREDICTION OF VC (EQN.6.5)- NYLON CYLINDERS

K= .652 S= 1.15

VAV	VC	RV	VC1	RV1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(L/D= 4)						
.619	.345	.5574	.2556	.4129	.3499	43100
1.074	.824	.7672	.8295	.7723	-6.6E-03	74800
1.733	1.694	.9775	1.6607	.9583	.02	120700
2.315	2.502	1.0808	2.3948	1.0345	.0447	161200
3.066	3.424	1.1168	3.3421	1.0901	.0245	213500
3.696	4.252	1.1504	4.1368	1.1193	.0279	257400
4.392	5.136	1.1694	5.0147	1.1418	.0242	305900
5.076	5.995	1.181	5.8775	1.1579	.02	353500
(L/D= 7)						
.676	.243	.3595	.2212	.3272	.0985	47100
1.045	.729	.6976	.7212	.6902	.0108	72800
1.771	1.654	.9339	1.705	.9627	-.0299	123300
2.37	2.49	1.0506	2.5166	1.0619	-.0106	165100
3.006	3.385	1.1261	3.3784	1.1239	1.9E-03	209400
3.641	4.214	1.1574	4.2389	1.1642	-5.9E-03	253600
4.331	5.16	1.1914	5.1738	1.1946	-2.7E-03	301600
4.966	5.98	1.2042	6.0343	1.2151	-9E-03	345900
(L/D= 10)						
1.045	.664	.6354	.6517	.6236	.0189	72800
1.733	1.603	.925	1.6275	.9391	-.0151	120700
2.426	2.53	1.0429	2.6104	1.076	-.0308	169000
3.033	3.412	1.125	3.4713	1.1445	-.0171	211200
3.707	4.36	1.1762	4.4273	1.1943	-.0152	258200
4.386	5.34	1.2175	5.3903	1.229	-9.3E-03	305500
(L/D= 14)						
1.074	.587	.5466	.6077	.5659	-.0341	74800
1.711	1.52	.8884	1.551	.9065	-.02	119200
2.37	2.466	1.0405	2.5268	1.0662	-.0241	165100
3.054	3.458	1.1323	3.5396	1.159	-.0231	212700
3.752	4.453	1.1868	4.5732	1.2189	-.0263	261300
4.362	5.401	1.2382	5.4764	1.2555	-.0138	303800

VC & RV: EXPERIMENTAL VC1 & RV1: EMPERICAL(EQUATION(6.5))
RE(D): FREE PIPE REYNOLDS NUMBER E:DEVIATION OF VC1 FROM VC

(D. 9) PREDICTION OF VC (EQN. 6. 5)- NYLON CYLINDERS

K= . 815 S= 1. 15

VAV	VC	RV	VC1	RV1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(L/D= 4)						
. 397	. 2082	. 5244	. 1885	. 4749	. 1043	27600
. 661	. 5224	. 7903	. 5122	. 7748	. 02	46000
1. 045	. 994	. 9512	. 9829	. 9406	. 0113	72800
1. 711	1. 761	1. 0292	1. 7993	1. 0516	-. 0213	119200
2. 453	2. 685	1. 0946	2. 7089	1. 1043	-8. 8E-03	170800
3. 143	3. 527	1. 1222	3. 5547	1. 131	-7. 8E-03	218900
3. 843	4. 433	1. 1535	4. 4128	1. 1483	4. 6E-03	267600
(L/D= 7)						
. 419	. 16	. 3819	. 1574	. 3756	. 0166	29200
. 675	. 472	. 6993	. 4945	. 7326	-. 0455	47000
1. 044	. 9543	. 9141	. 9804	. 9391	-. 0267	72700
1. 651	1. 702	1. 0309	1. 7798	1. 078	-. 0437	115000
2. 392	2. 613	1. 0924	2. 7556	1. 152	-. 0517	166600
3. 143	3. 664	1. 1658	3. 7446	1. 1914	-. 0215	218900
3. 806	4. 492	1. 1802	4. 6176	1. 2133	-. 0272	265100
(L/D= 10)						
. 661	. 45	. 6808	. 4397	. 6653	. 0233	46000
1. 039	. 903	. 8691	. 9608	. 9247	-. 0601	72400
1. 688	1. 796	1. 064	1. 8553	1. 0991	-. 032	117600
2. 508	2. 853	1. 1376	2. 9856	1. 1904	-. 0444	174700
3. 171	3. 777	1. 1911	3. 8995	1. 2297	-. 0314	220800
3. 861	4. 793	1. 2414	4. 8506	1. 2563	-. 0119	268900
(L/D= 14)						
. 661	. 407	. 6157	. 3935	. 5953	. 0344	46000
1. 039	. 89	. 8566	. 9374	. 9023	-. 0506	72400
1. 668	1. 781	1. 0677	1. 8426	1. 1047	-. 0334	116200
2. 508	2. 859	1. 14	3. 0514	1. 2167	-. 0631	174700
3. 171	3. 829	1. 2075	4. 0055	1. 2632	-. 0441	220800
3. 972	4. 98	1. 2538	5. 1582	1. 2986	-. 0345	276600

VC & RV: EXPERIMENTAL VC1 & RV1: EMPERICAL(EQUATION(6. 5))
RE(D): FREE PIPE REYNOLDS NUMBER E:DEVIATION OF VC1 FROM VC

(D. 10) PREDICTION OF VC (EQN. 6. 5)- ALUMINUM CYLINDERS

K= . 489   S= 2. 7

VAV	VC	RV	VC1	RV1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(L/D= 4)						
2. 381	. 4709	. 1978	. 4892	. 2055	-. 0374	165800
3. 055	1. 282	. 4196	1. 3712	. 4489	-. 0651	212800
3. 696	2. 1016	. 5686	2. 2101	. 598	-. 0491	257400
4. 362	3. 135	. 7187	3. 0817	. 7065	. 0173	303800
5. 076	4. 108	. 8093	4. 0161	. 7912	. 0229	353500
(L/D= 7)						
2. 778	. 4465	. 1607	. 4306	. 155	. 037	193500
3. 043	. 7964	. 2617	. 8031	. 2639	-8. 4E-03	211900
3. 347	1. 171	. 3439	1. 2305	. 3676	-. 0484	233100
3. 704	1. 664	. 4492	1. 7324	. 4677	-. 0395	258000
4. 258	2. 451	. 5756	2. 5113	. 5898	-. 024	296600
4. 696	3. 087	. 6574	3. 127	. 6659	-. 0128	327100
(L/D= 10)						
2. 978	. 1987	. 0667	. 2289	. 0769	-. 132	207400
3. 641	1. 156	. 3175	1. 2045	. 3308	-. 0403	253600
4. 331	2. 238	. 5167	2. 2199	. 5126	8. 2E-03	301600
4. 994	3. 129	. 6266	3. 1955	. 6399	-. 0208	347800
(L/D= 14)						
3. 696	. 7233	. 1957	. 7639	. 2067	-. 0531	257400
4. 331	1. 702	. 393	1. 7394	. 4016	-. 0215	301600
5. 022	2. 744	. 5464	2. 801	. 5577	-. 0204	349800

VC & RV: EXPERIMENTAL   VC1 & VR1: EMPERICAL(EQUATION(6. 5))
RE(D): FREE PIPE REYNOLDS NUMBER   E:DEVIATION OF VC1 FROM VC

(D. 11) PREDICTION OF VC (EQN. 6. 5)- ALUMINUM CYLINDERS

K= . 652 S= 2. 7

VAV	VC	RV	VC1	RV1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(L/D= 4)						
1. 756	. 335	. 1908	. 302	. 172	. 1093	122300
2. 343	1. 076	. 4592	1. 0424	. 4449	. 0322	163200
3. 06	2. 003	. 6546	1. 9468	. 6362	. 0289	213100
3. 729	2. 852	. 7648	2. 7907	. 7484	. 022	259700
4. 436	3. 773	. 8505	3. 6825	. 8301	. 0246	308900
5. 098	4. 626	. 9074	4. 5175	. 8861	. 024	355100
(L/D= 7)						
2. 183	. 2697	. 1235	. 4274	. 1958	-. 369	152000
2. 47	. 6233	. 2523	. 8163	. 3305	-. 2365	172000
2. 729	. 9833	. 3603	1. 1673	. 4277	-. 1576	190100
2. 923	1. 426	. 4879	1. 4302	. 4893	-2. 9E-03	203600
3. 42	2. 025	. 5921	2. 1036	. 6151	-. 0374	238200
3. 74	2. 498	. 6679	2. 5372	. 6784	-. 0155	260500
4. 358	3. 281	. 7529	3. 3746	. 7744	-. 0277	303500
4. 988	4. 241	. 8502	4. 2283	. 8477	3E-03	347400
(L/D= 10)						
2. 37	. 4051	. 1709	. 3368	. 1421	. 2028	165100
3. 033	1. 334	. 4398	1. 2771	. 4211	. 0445	211200
3. 673	2. 252	. 6131	2. 1849	. 5948	. 0307	255800
4. 359	3. 249	. 7454	3. 1579	. 7244	. 0289	303600
5. 076	4. 211	. 8296	4. 1748	. 8225	8. 7E-03	353500
(L/D= 14)						
3. 033	. 9427	. 3108	. 9123	. 3008	. 0333	211200
3. 696	1. 932	. 5227	1. 894	. 5125	. 02	257400
4. 414	2. 968	. 6724	2. 9572	. 67	3. 6E-03	307400
5. 054	4. 021	. 7956	3. 9049	. 7726	. 0297	352000

VC & RV: EXPERIMENTAL   VC1 & VR1: EMPERICAL(EQUATION(6. 5))
RE(D): FREE PIPE REYNOLDS NUMBER   E:DEVIATION OF VC1 FROM VC

(D.12) PREDICTION OF VC (EQN. 6.5)- ALUMINUM CYLINDERS

K= .815   S= 2.7

VAV	VC	RV	VC1	RV1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(L/D= 4)						
1.074	.256	.2384	.2307	.2148	.1095	74800
1.7	.9863	.5802	.9981	.5871	-.0118	118400
2.459	1.812	.7369	1.9285	.7843	-.0604	171300
3.116	2.73	.8761	2.7339	.8774	-1.4E-03	217000
3.861	3.716	.9624	3.6472	.9446	.0189	268900
(L/D= 7)						
1.33	.3923	.295	.315	.2369	.2452	92600
1.643	.701	.4267	.7272	.4426	-.0361	114400
2.012	1.161	.577	1.2131	.603	-.043	140100
2.481	1.783	.7187	1.8308	.7379	-.0261	172800
2.779	2.163	.7783	2.2232	.8	-.0271	193500
3.309	2.888	.8728	2.9211	.8828	-.0113	230500
(L/D= 10)						
1.756	.7141	.4067	.7036	.4007	.0149	122300
2.453	1.623	.6616	1.6644	.6785	-.0248	170800
3.171	2.592	.8174	2.654	.837	-.0234	220800
3.972	3.745	.9428	3.7581	.9462	-3.5E-03	276600
(L/D= 14)						
1.728	.602	.3484	.4553	.2635	.3222	120300
2.503	1.524	.6089	1.5706	.6275	-.0296	174300
3.171	2.527	.7969	2.5318	.7984	-1.9E-03	220800
4.049	3.811	.9412	3.7953	.9374	4.1E-03	282000
4.524	4.511	.9971	4.4789	.99	7.2E-03	315100

VC & RV: EXPERIMENTAL   VC1 & VR1: EMPERICAL(EQUATION(6.5))
RE(D): FREE PIPE REYNOLDS NUMBER   E:DEVIATION OF VC1 FROM VC

(D.13) PREDICTION OF VC (EQN. 6.9)- NYLON SPHERES

S= 1.15

VM	VC	VR	VC1	VR1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(K= .57)						
.3968	.1371	.3455	.0981	.2473	.3971	27600
1.0583	.8819	.8333	.8989	.8494	-.019	73700
1.7461	1.6327	.9351	1.7316	.9917	-.0571	121600
2.3811	2.3842	1.0013	2.5003	1.0501	-.0464	165800
3.0425	3.2327	1.0625	3.301	1.085	-.0207	211900
3.7039	4.048	1.0929	4.1017	1.1074	-.0131	258000
4.3653	4.8677	1.1151	4.9024	1.123	-7.1E-03	304000
(K= .652)						
.4365	.2267	.5194	.2141	.4904	.059	30400
1.0583	.9372	.8856	.9332	.8818	4.3E-03	73700
1.7461	1.6935	.9699	1.7287	.99	-.0203	121600
2.3811	2.4365	1.0233	2.4631	1.0344	-.0108	165800
3.0108	3.1711	1.0532	3.1913	1.06	-6.3E-03	209700
3.6736	3.9164	1.0661	3.9579	1.0774	-.0105	255900
4.3584	4.8046	1.1024	4.7499	1.0898	.0115	303500
(K= .815)						
.3968	.2869	.723	.2846	.7172	8.1E-03	27600
1.0847	1.0527	.9705	1.022	.9422	.03	75500
1.7594	1.7951	1.0203	1.7453	.992	.0285	122500
2.424	2.5267	1.0424	2.4578	1.0139	.028	168800
3.122	3.333	1.0676	3.2061	1.0269	.0396	217400
3.9262	4.1546	1.0582	4.0682	1.0362	.0212	273400
4.671	4.996	1.0696	4.8667	1.0419	.0266	325300

VC & RV: EXPERIMENTAL VC1 & RV1: EMPERICAL(EQUATION(6.9))
RE(D): FREE PIPE REYNOLDS NUMBER E: DEVIATION OF VC1 FROM VC

(D.14) PREDICTION OF VC (EQN. 6.9)- ALUMINUM SPHERES

S= 2.7

VM	VC	VR	VC1	VR1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(K= .57)						
1.7561	.7816	.4451	.7338	.4178	.0652	122300
2.3978	1.4962	.624	1.5106	.63	-9.5E-03	167000
3.0605	2.265	.7401	2.3129	.7557	-.0207	213200
3.6957	3.0709	.8309	3.0819	.8339	-3.6E-03	257400
4.4136	4.07	.9221	3.9509	.8952	.0301	307400
5.1316	4.868	.9486	4.8202	.9393	9.9E-03	357400
(K= .652)						
.9597	.1829	.1906	.051	.0531	2.5898	66800
1.4717	.6685	.4542	.6431	.437	.0395	102500
2.0405	1.2925	.6334	1.3009	.6376	-6.5E-03	142100
2.3811	1.665	.6993	1.6948	.7118	-.0176	165800
2.7568	2.0871	.7571	2.1293	.7724	-.0198	192000
3.1936	2.5432	.7963	2.6345	.8249	-.0347	222400
3.6113	3.118	.8634	3.1176	.8633	1E-04	251500
4.0823	3.7152	.9101	3.6623	.8971	.0144	284300
4.5793	4.2797	.9346	4.2371	.9253	.0101	318900
4.966	4.8043	.9674	4.6843	.9433	.0256	345900
(K= .815)						
1.0318	.5829	.5649	.5933	.575	-.0176	71900
1.7276	1.1932	.6907	1.3392	.7752	-.1091	120300
2.4254	1.901	.7838	2.0873	.8606	-.0893	168900
3.1434	2.7976	.89	2.857	.9089	-.0208	218900
3.9632	3.8127	.962	3.7359	.9426	.0206	276000
4.8598	4.732	.9737	4.6971	.9665	7.4E-03	338500

VC & RV: EXPERIMENTAL VC1 & RV1: EMPERICAL(EQUATION(6.9))
RE(D): FREE PIPE REYNOLDS NUMBER E: DEVIATION OF VC1 FROM VC

(D. 15) PREDICTION OF VC (EQN. 6. 9)- STEEL SPHERES

S= 7. 82

VM	VC	VR	VC1	VR1	E	RE(D)
(M/S)	(M/S)	(-)	(M/S)	(-)	(-)	(-)
(K= . 57)						
3. 088	. 895	. 2898	. 9041	. 2928	-. 0101	215100
3. 4473	1. 229	. 3565	1. 3391	. 3884	-. 0822	240100
3. 9167	1. 8826	. 4807	1. 9073	. 487	-. 013	272800
4. 3309	2. 3287	. 5377	2. 4088	. 5562	-. 0332	301600
4. 8555	3	. 6179	3. 0438	. 6269	-. 0144	338200
(K= . 652)						
2. 315	. 5037	. 2176	. 5215	. 2253	-. 0341	161200
2. 6818	. 8222	. 3066	. 9457	. 3526	-. 1306	186800
2. 9764	1. 2306	. 4135	1. 2864	. 4322	-. 0434	207300
3. 4747	1. 8612	. 5356	1. 8627	. 5361	-8E-04	242000
3. 889	2. 3798	. 6119	2. 3418	. 6022	. 0162	270900
4. 3915	2. 9443	. 6705	2. 923	. 6656	7. 3E-03	305800
4. 8555	3. 4805	. 7168	3. 4596	. 7125	6E-03	338200
(K= . 815)						
1. 9842	. 89	. 4485	1. 0832	. 5459	-. 1783	138200
2. 4254	1. 3492	. 5563	1. 5561	. 6416	-. 133	168900
2. 812	1. 7904	. 6367	1. 9706	. 7008	-. 0914	195800
3. 1796	2. 1936	. 6899	2. 3647	. 7437	-. 0723	221400
3. 5854	2. 7023	. 7537	2. 7997	. 7809	-. 0348	249700
3. 9718	3. 147	. 7923	3. 2139	. 8092	-. 0208	276600
4. 4136	3. 5616	. 807	3. 6876	. 8355	-. 0342	307400

VC & RV: EXPERIMENTAL VC1 & RV1: EMPERICAL(EQUATION(6.9))
RE(D): FREE PIPE REYNOLDS NUMBER E. DEVIATION OF VC1 FROM VC

(D.16) PREDICTION OF (DP/L)C (EQNS. 6.13 & 6.14)

NYLON CYLINDER

K= .489 S= 1.15

VAV (M/S)	(DPO/L) (KPA/M)	(DP/L)L (KPA/M)	(DP/L)C (KPA/M)	F (-)	(DPO/L)* (KPA/M)	(DP/L)L* (KPA/M)	(DP/L)C* (KPA/M)	E (-)
(L/D= 4)								
1.058	.4523	.1481	.6004	.021	.4536	.1509	.6044	-6.7E-03
1.728	.4523	.3458	.7981	.0188	.4536	.3603	.8139	-.0194
2.403	.4523	.654	1.1063	.018	.4536	.6671	1.1207	-.0129
3.01	.4523	.9871	1.4394	.0174	.4536	1.0118	1.4654	-.0178
3.696	.4523	1.456	1.9083	.017	.4536	1.4905	1.9441	-.0184
4.386	.4523	2.048	2.5003	.0166	.4536	2.0496	2.5032	-1.2E-03
5.077	.4523	2.715	3.1673	.0163	.4536	2.6967	3.1503	5.4E-03
(L/D= 7)								
1.045	.4911	.1555	.6466	.021	.4536	.1472	.6008	.0762
1.722	.4911	.3455	.8366	.0188	.4536	.3578	.8114	.031
2.37	.4911	.6416	1.1327	.018	.4536	.6489	1.1025	.0274
2.95	.4911	.9131	1.4042	.0174	.4536	.9719	1.4255	-.015
3.696	.4911	1.481	1.9721	.017	.4536	1.4905	1.9441	.0144
4.303	.4911	2.05	2.5411	.0166	.4536	1.9728	2.4264	.0473
4.988	.4911	2.715	3.2061	.0163	.4536	2.603	3.0566	.0489
(L/D= 10)								
1.098	.4523	.1481	.6004	.0203	.4536	.1571	.6107	-.0168
1.711	.4523	.3331	.7854	.0188	.4536	.3533	.8069	-.0266
2.371	.4523	.6293	1.0816	.0179	.4536	.6459	1.0995	-.0163
3.033	.4523	.9624	1.4147	.0174	.4536	1.0274	1.481	-.0447
3.696	.4523	1.456	1.9083	.018	.4536	1.5782	2.0318	-.0608
4.386	.4523	1.851	2.3033	.0166	.4536	2.0496	2.5032	-.0799
5.02	.4523	2.61	3.0623	.0163	.4536	2.6365	3.0901	-9E-03
(L/D= 14)								
1.098	.42	.1646	.5846	.0205	.4536	.1586	.6122	-.0451
1.728	.42	.3497	.7697	.0188	.4536	.3603	.8139	-.0543
2.371	.42	.6376	1.0576	.018	.4536	.6495	1.1031	-.0412
3.006	.42	1.041	1.461	.0174	.4536	1.0092	1.4628	-1.2E-03
3.694	.42	1.481	1.901	.0169	.4536	1.4802	1.9338	-.017
4.41[illegible]	.42	2.139	2.559	.0166	.4536	2.0759	2.5295	.0117
5.022	.42	2.797	3.217	.0163	.4536	2.6386	3.0922	.0404

(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE — F: PIPE FRICTION FACTOR
*: EMPERICAL VALUES (BY EQUATIONS(6.13) & (6.14)) — M=METER
E: DEVIATION OF EMPERICAL VALUE FROM EXPERIMENT — S=SECOND PA=PASCAL

(D.17) PREDICTION OF (DP/L)C (EQNS. 6.13 & 6.14)

NYLON CYLINDER

K= .652 S= 1.15

VAV	(DPO/L)	(DP/L)L	(DP/L)C	F	(DPO/L)*	(DP/L)L*	(DP/L)C*	E
(M/S)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)								
.619	.7803	.0617	.842	.023	.7701	.0566	.8266	.0186
1.074	.7803	.1678	.9481	.0205	.7701	.1518	.9219	.0284
1.733	.7803	.3702	1.1505	.0188	.7701	.3624	1.1325	.0159
2.315	.7803	.6416	1.4219	.018	.7701	.6192	1.3893	.0235
3.066	.8142	1.061	1.8752	.0173	.7701	1.0438	1.8139	.0338
3.696	.8142	1.53	2.3442	.0169	.7701	1.4818	2.2519	.041
4.392	.8142	1.974	2.7882	.0166	.7701	2.0553	2.8254	-.0132
5.076	.8142	2.715	3.5292	.0163	.7701	2.6957	3.4658	.0183
(L/D= 7)								
.676	.7754	.0617	.8371	.023	.7701	.0675	.8376	-6E-04
1.045	.7754	.1481	.9235	.021	.7701	.1472	.9173	6.8E-03
1.768	.7754	.39	1.1654	.0188	.7701	.3772	1.1473	.0158
2.371	.7754	.6416	1.417	.018	.7701	.6495	1.4196	-1.8E-03
3.006	.8336	1.04	1.8736	.0174	.7701	1.0092	1.7793	.053
3.64	.8336	1.456	2.2896	.017	.7701	1.4457	2.2158	.0333
4.331	.8336	1.851	2.6846	.0166	.7701	1.9986	2.7687	-.0304
(L/D= 10)								
1.045	.7464	.1357	.8821	.0205	.7701	.1437	.9138	-.0347
1.733	.7464	.3455	1.0919	.019	.7701	.3663	1.1364	-.0391
2.427	.7464	.6169	1.3633	.018	.7701	.6805	1.4506	-.0602
3.033	.7464	.9377	1.6841	.0174	.7701	1.0274	1.7975	-.0631
3.706	.7735	1.431	2.2045	.017	.7701	1.4986	2.2687	-.0283
4.386	.7735	1.925	2.6985	.0166	.7701	2.0496	2.8197	-.043
(L/D= 14)								
1.074	.727	.1851	.9121	.0205	.7701	.1518	.9219	-.0106
1.711	.727	.3908	1.1178	.0188	.7701	.3533	1.1234	-4.9E-03
2.37	.727	.6171	1.3441	.018	.7701	.6489	1.419	-.0528
3.054	.727	1.029	1.756	.0173	.7701	1.0357	1.8058	-.0276
3.752	.727	1.44	2.167	.0168	.7701	1.518	2.2881	-.0529
4.362	.7754	2.098	2.8734	.0166	.7701	2.0273	2.7974	.0272

(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE F: PIPE FRICTION FACTOR
*: EMPERICAL VALUES (BY EQUATIONS(6.13) & (6.14)) M=METER
E: DEVIATION OF EMPERICAL VALUE FROM EXPERIMENT S=SECOND PA=PASCAL

(D. 18) PREDICTION OF (DP/L)C (EQNS. 6. 13 & 6. 14)

NYLON CYLINDER

K= . 815 S= 1. 15

VAV (M/S)	(DPO/L) (KPA/M)	(DP/L)L (KPA/M)	(DP/L)C (KPA/M)	F (-)	(DPO/L)* (KPA/M)	(DP/L)L* (KPA/M)	(DP/L)C* (KPA/M)	E (-)
(L/D= 4)								
. 397	1. 154	. 0388	1. 1848	. 024	1. 161	. 0243	1. 1853	-4E-04
. 661	1. 154	. 0864	1. 2404	. 023	1. 161	. 0645	1. 2255	. 0122
1. 045	1. 154	. 1604	1. 3144	. 0205	1. 161	. 1437	1. 3047	7. 4E-03
1. 711	1. 154	. 3516	1. 5056	. 0188	1. 161	. 3533	1. 5143	-5. 7E-03
2. 453	1. 154	. 7107	1. 8647	. 0179	1. 161	. 6913	1. 8523	6. 7E-03
3. 143	1. 154	1. 086	2. 24	. 0173	1. 161	1. 0969	2. 2579	-7. 9E-03
3. 834	1. 221	1. 555	2. 776	. 0168	1. 161	1. 5851	2. 7461	. 0109
(L/D= 7)								
. 419	1. 163	. 0321	1. 1951	. 024	1. 161	. 027	1. 188	5. 9E-03
. 675	1. 163	. 0617	1. 2247	. 023	1. 161	. 0673	1. 2283	-2. 9E-03
1. 044	1. 163	. 1604	1. 3234	. 0205	1. 161	. 1434	1. 3044	. 0146
1. 651	1. 132	. 3331	1. 4651	0189	1. 161	. 3307	1. 4917	-. 0178
2. 392	1. 132	. 6416	1. 7736	. 018	1. 161	. 661	1. 822	-. 0266
3. 143	1. 163	1. 074	2. 237	. 0173	1. 161	1. 0969	2. 2579	-9. 3E-03
3. 806	1. 163	1. 604	2. 767	. 0168	1. 161	1. 562	2. 723	. 0162
(L/D= 10)								
. 662	1. 14	. 0691	1. 2091	. 023	1. 161	. 0646	1. 2256	-. 0135
1. 039	1. 14	. 1431	1. 2831	. 0205	1. 161	. 142	1. 303	-. 0153
1. 688	1. 14	. 3146	1. 4546	. 0188	1. 161	. 3438	1. 5048	-. 0334
2. 51	1. 087	. 642	1. 729	. 018	1. 161	. 7279	1. 8889	-. 0846
3. 171	1. 167	1. 036	2. 203	. 0173	1. 161	1. 1165	2. 2775	-. 0327
3. 861	1. 167	1. 57	2. 737	. 0166	1. 161	1. 5883	2. 7493	-4. 5E-03
(L/D= 14)								
. 661	1. 124	. 0617	1. 1857	. 023	1. 161	. 0646	1. 2256	-. 0325
1. 039	1. 124	. 1337	1. 2577	. 0205	1. 161	. 142	1. 303	-. 0348
1. 668	1. 086	. 3291	1. 4151	. 0189	1. 161	. 3375	1. 4985	-. 0557
2. 508	1. 047	. 6788	1. 7258	. 0178	1. 161	. 7186	1. 8796	-. 0818
3. 171	1. 086	1. 111	2. 197	. 0173	1. 161	1. 1165	2. 2775	-. 0354
3. 972	1. 163	1. 811	2. 974	. 0168	1. 161	1. 7012	2. 8622	. 0391

(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE F: PIPE FRICTION FACTOR
*: EMPERICAL VALUES (BY EQUATIONS(6. 13) & (6. 14)) M=METER
E: DEVIATION OF EMPERICAL VALUE FROM EXPERIMENT S=SECOND PA=PASCAL

(D.19) PREDICTION OF (DP/L)C (EQNS. 6.13 & 6.14)

ALUMINUM CYLINDER

K= .489 S= 2.7

VAV	(DPO/L)	(DP/L)L	(DP/L)C	F	(DPO/L)*	(DP/L)L*	(DP/L)C*	E
(M/S)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)								
2.381	5.202	.6412	5.8432	.0179	5.1404	.6513	5.7917	8.9E-03
3.054	5.202	1.036	6.238	.0173	5.1404	1.0357	6.1761	.01
3.696	5.202	1.456	6.658	.0169	5.1404	1.4818	6.6222	5.4E-03
4.362	5.202	1.974	7.176	.0166	5.1404	2.0273	7.1677	1.2E-03
5.078	5.202	2.665	7.867	.0163	5.1404	2.6978	7.8382	3.7E-03
(L/D= 7)								
2.778	4.911	.8367	5.7477	.0175	5.1404	.8668	6.0072	-.0432
3.042	5.041	1.049	6.09	.0173	5.1404	1.0275	6.1679	-.0126
3.347	5.169	1.357	6.526	.0171	5.1404	1.2295	6.3699	.0245
3.704	5.169	1.53	6.699	.0169	5.1404	1.4882	6.6286	.0106
4.258	5.169	1.99	7.159	.0166	5.1404	1.9318	7.0722	.0123
4.696	5.169	2.418	7.587	.0165	5.1404	2.3355	7.4759	.0149
(L/D= 10)								
2.978	4.976	1.012	5.988	.018	5.1404	1.0246	6.165	-.0287
3.641	4.976	1.407	6.383	.0176	5.1404	1.4976	6.638	-.0384
4.331	4.976	1.851	6.827	.0175	5.1404	2.1069	7.2473	-.058
4.994	4.976	2.789	7.765	.0171	5.1404	2.7373	7.8777	-.0143
(L/D= 14)								
3.696	4.847	1.481	6.328	.0169	5.1404	1.4818	6.6222	-.0444
4.331	4.847	2.16	7.007	.0166	5.1404	1.9986	7.139	-.0185
5.022	4.847	2.571	7.418	.0163	5.1404	2.6386	7.779	-.0464

(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE F: PIPE FRICTION FACTOR
*: EMPERICAL VALUES (BY EQUATION(6.13) & (6.14)) M=METER
E: DEVIATION OF EMPERICAL VALUE FROM EXPERIMENT S=SECOND PA=PASCAL

(D. 20) PREDICTION OF (DP/L)C (EQNS. 6.13 & 6.14)

ALUMINUM CYLINDER

K= .652 S= 2.7

VAV	(DPO/L)	(DP/L)L	(DP/L)C	F	(DPO/L)*	(DP/L)L*	(DP/L)C*	E
(M/S)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)								
1.756	8.99	.3455	9.3355	.0188	8.7274	.3721	9.0995	.0259
2.343	8.99	.617	9.607	.018	8.7274	.6342	9.3616	.0262
3.06	8.99	.9254	9.9154	.0173	8.7274	1.0397	9.7671	.0152
3.729	8.99	1.481	10.471	.0169	8.7274	1.5084	10.2358	.023
4.436	9.16	2.036	11.196	.0166	8.7274	2.0966	10.824	.0344
5.098	9.16	2.899	12.059	.0163	8.7274	2.7191	11.4465	.0535
(L/D= 7)								
2.183	8.918	.531	9.449	.0182	8.7274	.5567	9.2841	.0178
2.47	8.918	.691	9.609	.0178	8.7274	.697	9.4244	.0196
2.729	8.918	.839	9.757	.0176	8.7274	.8413	9.5687	.0197
2.922	8.918	.987	9.905	.0174	8.7274	.9535	9.6809	.0231
3.42	8.918	1.283	10.201	.0171	8.7274	1.2838	10.0112	.019
3.74	9.111	1.555	10.666	.0169	8.7274	1.5173	10.2447	.0411
4.358	9.111	2.18	11.291	.0166	8.7274	2.0236	10.751	.0502
(L/D= 10)								
2.37	8.956	.617	9.573	.018	8.7274	.6489	9.3763	.021
3.033	8.956	1.036	9.992	.0173	8.7274	1.0215	9.7489	.0249
3.673	8.956	1.481	10.437	.0169	8.7274	1.4634	10.1908	.0242
4.359	8.956	2.036	10.992	.0166	8.7274	2.0245	10.7519	.0223
5.076	8.956	2.764	11.72	.0163	8.7274	2.6957	11.4231	.026
(L/D= 14)								
3.033	8.966	1.029	9.995	.0173	8.7274	1.0215	9.7489	.0252
3.696	9.015	1.543	10.558	.0169	8.7274	1.4818	10.2092	.0342
4.414	9.208	2.16	11.368	.0166	8.7274	2.0759	10.8033	.0523
5.054	9.208	2.88	12.088	.0163	8.7274	2.6723	11.3997	.0604

(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE F: PIPE FRICTION FACTOR
*: EMPERICAL VALUES (BY EQUATION(6.13) & (6.14)) M=METER
E: DEVIATION OF EMPERICAL VALUE FROM EXPERIMENT S=SECOND PA=PASCAL

(D. 21) PREDICTION OF (DP/L)C (EQNS. 6. 13 & 6. 14)

ALUMINUM CYLINDER

K= . 815 S= 2. 7

VAV	(DPO/L)	(DP/L)L	(DP/L)C	F	(DPO/L)*	(DP/L)L*	(DP/L)C*	E
(M/S)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)
(L/D= 4)								
1. 074	13. 027	. 1604	13. 1874	. 0205	13. 1583	. 1518	13. 3101	-9. 2E-03
1. 699	13. 027	. 3948	13. 4218	. 019	13. 1583	. 352	13. 5103	-6. 6E-03
2. 458	12. 892	. 654	13. 546	. 018	13. 1583	. 698	13. 8563	-. 0224
3. 116	12. 892	1. 086	13. 978	. 0173	13. 1583	1. 0781	14. 2364	-. 0182
3. 861	12. 892	1. 604	14. 496	. 0168	13. 1583	1. 6075	14. 7658	-. 0183
(L/D= 7)								
1. 33	12. 795	. 1974	12. 9924	. 0197	13. 1583	. 2237	13. 382	-. 0291
1. 643	12. 795	. 3085	13. 1035	. 019	13. 1583	. 3292	13. 4875	-. 0285
2. 012	12. 795	. 4689	13. 2639	. 0184	13. 1583	. 4781	13. 6364	-. 0273
2. 481	12. 795	. 6786	13. 4736	. 0178	13. 1583	. 7032	13. 8615	-. 028
2. 779	12. 795	. 8637	13. 6587	. 0175	13. 1583	. 8675	14. 0258	-. 0262
3. 309	12. 872	1. 197	14. 069	. 0172	13. 1583	1. 2088	14. 3671	-. 0207
(L/D= 10)								
1. 756	13. 027	. 3578	13. 3848	. 0188	13. 1583	. 3721	13. 5304	-. 0108
2. 453	13. 027	. 6786	13. 7056	. 0179	13. 1583	. 6913	13. 8496	-. 0104
3. 171	13. 027	1. 061	14. 088	. 0172	13. 1583	1. 1101	14. 2684	-. 0126
3. 972	13. 027	1. 703	14. 73	. 0168	13. 1583	1. 7012	14. 8595	-8. 7E-03
(L/D= 14)								
1. 728	12. 989	. 3702	13. 3592	. 0188	13. 1583	. 3603	13. 5186	-. 0118
2. 503	12. 989	. 6994	13. 6884	. 0178	13. 1583	. 7158	13. 8741	-. 0134
3. 171	12. 989	1. 111	14. 1	. 0172	13. 1583	1. 1101	14. 2684	-. 0118
4. 049	13. 182	1. 913	15. 095	. 0167	13. 1583	1. 7573	14. 9156	. 012
4. 524	12. 989	2. 304	15. 293	. 0165	13. 1583	2. 1675	15. 3258	-2. 1E-03

(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE F: PIPE FRICTION FACTOR
*: EMPERICAL VALUES (BY EQUATION(6. 13) & (6. 14)) M=METER
E: DEVIATION OF EMPERICAL VALUE FROM EXPERIMENT S=SECOND PA=PASCAL

(D. 22) PRESS. RATIO & UNIT ENERGY - NYLON CYLINDERS

K= .489 S= 1.15

VAV	VC	RV	(DPO/L)	(DP/L)L	(DP/L)C	RP	P
(M/S)	(M/S)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	KW-S/KG-M
(L/D= 4)							
1.058	.769	.7268	.4523	.1481	.6004	4.054	3.0039
1.728	1.636	.9468	.4523	.3458	.7981	2.308	3.0655
2.403	2.51	1.0445	.4523	.654	1.1063	1.6916	3.8516
3.006	3.34	1.1111	.4523	.9871	1.4394	1.4582	4.7109
3.696	4.196	1.1353	.4523	1.456	1.9083	1.3106	6.1126
4.386	5.03	1.1468	.4523	2.048	2.5003	1.2208	7.9282
5.077	5.892	1.1605	.4523	2.715	3.1673	1.1666	9.9247
(L/D= 7)							
1.045	.605	.5789	.4911	.1555	.6466	4.1582	4.0614
1.722	1.454	.8444	.4911	.3455	.8366	2.4214	3.6031
2.37	2.4	1.0127	.4911	.6416	1.1327	1.7654	4.0676
2.95	3.234	1.0963	.4911	.9131	1.4042	1.5378	4.658
3.696	4.23	1.1445	.4911	1.481	1.9721	1.3316	6.2662
4.303	5.063	1.1766	.4911	2.05	2.5411	1.2396	7.8536
4.988	5.919	1.1866	.4911	2.715	3.2061	1.1809	9.8252
(L/D= 10)							
1.098	.519	.4727	.4523	.1481	.6004	4.054	4.6191
1.711	1.407	.8223	.4523	.3331	.7854	2.3579	3.4732
2.371	2.366	.9979	.4523	.6293	1.0816	1.7187	3.9416
3.033	3.347	1.1035	.4523	.9624	1.4147	1.47	4.6619
3.696	4.29	1.1607	.4523	1.456	1.9083	1.3106	5.9787
4.386	5.288	1.2057	.4523	1.851	2.3033	1.2444	6.9472
5.02	6.232	1.2414	.4523	2.61	3.0623	1.1733	8.9703
(L/D= 14)							
1.098	.347	.316	.42	.1646	.5846	3.5516	6.7269
1.728	1.316	.7616	.42	.3497	.7697	2.201	3.6753
2.371	2.34	.9869	.42	.6376	1.0576	1.6587	3.8969
3.006	3.33	1.1078	.42	1.041	1.461	1.4035	4.796
3.694	4.325	1.1708	.42	1.481	1.901	1.2836	5.9044
4.414	5.439	1.2322	.42	2.139	2.559	1.1964	7.5521
5.022	6.363	1.267	.42	2.7974	3.2174	1.1501	9.2343

(DPO/L) & (DP/L)L: PRESS. GRADIENT DUE TO CAPSULE & WATER RESPECTIVELY
(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE (=(DPO/L)+(DP/L)L)
RP. PRESS. RATIO(=(DP/L)C/(DP/L)L). P:UNIT ENERGY FOR CAPSULE(EQN. (6.18)
M=METER S=SECOND PA=PASCAL W=WATT KG=KILOGRAM

(D. 23) PRESS. RATIO & UNIT ENERGY – NYLON CYLINDERS

K= .652   S= 1.15

VAV	VC	RV	(DPO/L)	(DP/L)L	(DP/L)C	RP	P
(M/S)	(M/S)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	KW-S/KG-M
(L/D= 4)							
.619	.345	.5574	.7803	.0617	.842	13.6467	3.0902
1.074	.824	.7672	.7803	.1678	.9481	5.6502	2.5278
1.733	1.694	.9775	.7803	.3702	1.1505	3.1078	2.4076
2.315	2.502	1.0808	.7803	.6416	1.4219	2.2162	2.6912
3.066	3.424	1.1168	.8142	1.061	1.8752	1.7674	3.4347
3.696	4.252	1.1504	.8142	1.53	2.3442	1.5322	4.1681
4.392	5.136	1.1694	.8142	1.974	2.7882	1.4125	4.8772
5.076	5.995	1.181	.8142	2.715	3.5292	1.2999	6.1125
(L/D= 7)							
.676	.243	.3595	.7754	.0617	.8371	13.5673	4.7635
1.045	.729	.6976	.7754	.1481	.9235	6.2357	2.7079
1.768	1.654	.9355	.7754	.3899	1.1653	2.9887	2.548
2.371	2.49	1.0502	.7754	.6416	1.417	2.2085	2.76
3.006	3.385	1.1261	.8336	1.036	1.8696	1.8046	3.3961
3.641	4.22	1.159	.8336	1.456	2.2896	1.5725	4.0409
4.331	5.16	1.1914	.8336	1.851	2.6846	1.4504	4.6092
(L/D= 10)							
1.045	.664	.6354	.7464	.1357	.8821	6.5004	2.8397
1.733	1.603	.925	.7464	.3455	1.0919	3.1603	2.4147
2.427	2.53	1.0424	.7464	.6169	1.3633	2.2099	2.6751
3.033	3.412	1.125	.7464	.9377	1.6841	1.796	3.0622
3.706	4.36	1.1765	.7735	1.431	2.2045	1.5405	3.833
4.386	5.34	1.2175	.7735	1.925	2.6985	1.4018	4.5337
(L/D= 14)							
1.074	.587	.5466	.727	.1851	.9121	4.9276	3.4136
1.711	1.52	.8884	.727	.3908	1.1178	2.8603	2.5738
2.37	2.466	1.0405	.727	.6171	1.3441	2.1781	2.6424
3.054	3.458	1.1323	.727	1.029	1.756	1.7065	3.1723
3.752	4.453	1.1868	.727	1.44	2.167	1.5049	3.7349
4.362	5.401	1.2382	.7754	2.098	2.8734	1.3696	4.7469

(DPO/L) & (DP/L)L: PRESS. GRADIENT DUE TO CAPSULE & WATER RESPECTIVELY
(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE (=(DPO/L)+(DP/L)L)
RP: PRESS. RATIO(=(DP/L)C/(DP/L)L)   P:UNIT ENERGY FOR CAPSULE(EQN. (6.18)
M=METER   S=SECOND   PA=PASCAL   W=WATT   KG=KILOGRAM

(D.24) PRESS. RATIO & UNIT ENERGY - NYLON CYLINDERS

K= .815 S= 1.15

VAV	VC	RV	(DPO/L)	(DP/L)L	(DP/L)C	RP	P
(M/S)	(M/S)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	KW-S/KG-M
(L/D= 4)							
.397	.208	.5239	1.154	.0308	1.1848	38.4675	2.9605
.661	.522	.7897	1.154	.0864	1.2404	14.3565	2.0563
1.045	.994	.9512	1.154	.1604	1.3144	8.1945	1.809
1.711	1.761	1.0292	1.154	.3516	1.5056	4.2821	1.9151
2.453	2.685	1.0946	1.154	.7107	1.8647	2.6238	2.2302
3.143	3.527	1.1222	1.154	1.086	2.24	2.0626	2.6132
3.834	4.433	1.1562	1.221	1.555	2.776	1.7852	3.1431
(L/D= 7)							
.419	.16	.3819	1.163	.0321	1.1951	37.2305	4.0972
.675	.472	.6993	1.163	.0617	1.2247	19.8493	2.2929
1.044	.954	.9138	1.163	.1604	1.3234	8.2506	1.896
1.651	1.702	1.0309	1.132	.3331	1.4651	4.3984	1.8606
2.392	2.613	1.0924	1.132	.6416	1.7736	2.7643	2.1255
3.143	3.664	1.1658	1.163	1.074	2.237	2.0829	2.5121
3.806	4.492	1.1802	1.163	1.604	2.767	1.7251	3.0692
(L/D= 10)							
.662	.45	.6801	1.14	.0691	1.2091	17.4978	2.3275
1.039	.903	.8691	1.14	.1431	1.2831	8.9665	1.9327
1.688	1.796	1.064	1.14	.3146	1.4546	4.6236	1.7898
2.508	2.853	1.1376	1.087	.642	1.729	2.6931	1.9898
3.171	3.777	1.1911	1.167	1.036	2.203	2.1264	2.4213
3.861	4.793	1.2414	1.167	1.579	2.746	1.7391	2.8959
(L/D= 14)							
.661	.407	.6154	1.124	.0617	1.1857	19.2172	2.5225
1.039	.89	.8566	1.124	.1337	1.2577	9.4069	1.9222
1.668	1.781	1.0677	1.086	.3291	1.4151	4.2999	1.735
2.508	2.853	1.1376	1.047	.6788	1.7258	2.5424	1.9861
3.171	3.829	1.2075	1.086	1.111	2.197	1.9775	2.3819
3.972	4.98	1.2538	1.163	1.811	2.974	1.6422	3.1053

(DPO/L) & (DP/L)L: PRESS. GRADIENT DUE TO CAPSULE & WATER RESPECTIVELY
(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE (=(DPO/L)+(DP/L)L)
RP: PRESS. RATIO(=(DP/L)C/(DP/L)L) P:UNIT ENERGY FOR CAPSULE(EQN. (6.18)
M=METER S=SECOND PA=PASCAL W=WATT KG=KILOGRAM

(D.25) PRESS. RATIO & UNIT ENERGY - ALUMINUM CYLINDERS

K= .489 S= 2.7

VAV	VC	RV	(DPO/L)	(DP/L)L	(DP/L)C	RP	P
(M/S)	(M/S)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	KW-S/KG-M
(L/D= 4)							
2.381	.471	.1978	5.202	.6412	5.8432	9.1129	45.7518
3.054	1.282	.4198	5.202	1.036	6.238	6.0212	15.5363
3.696	2.102	.5687	5.202	1.456	6.658	4.5728	12.2395
4.362	3.135	.7187	5.202	1.974	7.176	3.6353	10.4389
5.078	4.108	.809	5.202	2.665	7.867	2.952	10.167
(L/D= 7)							
2.778	.447	.1609	4.911	.8367	5.7477	6.8695	29.8766
3.042	.796	.2617	5.041	1.049	6.09	5.8055	24.3324
3.347	1.171	.3499	5.169	1.357	6.526	4.8091	19.5015
3.704	1.664	.4492	5.169	1.53	6.699	4.3784	15.5901
4.258	2.451	.5756	5.169	1.99	7.159	3.5975	13.0028
4.696	3.087	.6574	5.169	2.418	7.587	3.1377	12.0666
(L/D= 10)							
2.978	.199	.0668	4.976	1.012	5.988	5.917	93.6862
3.641	1.156	.3175	4.976	1.407	6.383	4.5366	16.8151
4.331	2.238	.5167	4.976	1.851	6.827	3.6883	13.8128
4.994	3.129	.6266	4.976	2.789	7.765	2.7842	12.9571
(L/D= 14)							
3.696	.723	.1956	4.847	1.481	6.328	4.2728	33.8207
4.331	1.702	.393	4.847	2.16	7.007	3.244	18.6416
5.022	2.744	.5464	4.847	2.571	7.418	2.8853	11.3551

(DPO/L) & (DP/L)L: PRESS. GRADIENT DUE TO CAPSULE & WATER RESPECTIVELY
(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE (=(DPO/L)+(DP/L)L)
RP: PRESS. RATIO((DP/L)C/(DP/L)L) P: UNIT ENERGY FOR CAPSULE(EQN. 6.18)
M=METER S=SECOND PA=PASCAL W=WATT KG=KILOGRAM

(D. 26) PRESS. RATIO & UNIT ENERGY - ALUMINUM CYLINDERS

K= .652 S= 2.7

VAV	VC	RV	(DPO/L)	(DP/L)L	(DP/L)C	RP	P
(M/S)	(M/S)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	KW-S/KG-M
(L/D= 4)							
1.756	.335	.1908	8.99	.3455	9.3355	27.0203	42.6342
2.343	1.076	.4592	8.99	.617	9.607	15.5705	16.4033
3.06	2.003	.6546	8.99	.9254	9.9154	10.7147	11.8778
3.729	2.852	.7648	8.99	1.481	10.471	7.0702	10.7353
4.436	3.773	.8505	9.16	2.036	11.196	5.499	7.7413
5.098	4.626	.9074	9.16	2.899	12.059	4.1597	6.2523
(L/D= 7)							
2.183	.269	.1232	8.918	.531	9.449	17.7947	45.0954
2.47	.623	.2522	8.918	.691	9.609	13.9059	29.8724
2.729	.983	.3602	8.918	.839	9.757	11.6293	21.2398
2.922	1.426	.488	8.918	.987	9.905	10.0355	15.9147
3.42	2.025	.5921	8.918	1.283	10.201	7.9509	13.5091
3.74	2.498	.6679	9.111	1.555	10.666	6.8592	9.3913
4.358	3.281	.7529	9.111	2.18	11.291	5.1794	8.8198
(L/D= 10)							
2.37	.405	.1709	8.956	.617	9.573	15.5154	32.9447
3.033	1.334	.4398	8.956	1.036	9.992	9.6448	17.8136
3.673	2.252	.6131	8.956	1.481	10.437	7.0473	10.0109
4.359	3.249	.7454	8.956	2.036	10.992	5.3988	8.6728
5.076	4.211	.8296	8.956	2.764	11.72	4.2402	8.3082
(L/D= 14)							
3.033	.943	.3109	8.966	1.029	9.995	9.7133	18.9055
3.696	1.932	.5227	9.015	1.543	10.558	6.8425	11.8782
4.414	2.968	.6724	9.208	2.16	11.368	5.263	9.9425
5.054	4.021	.7956	9.208	2.88	12.088	4.1972	7.1481

(DPO/L) & (DP/L)L: PRESS. GRADIENT DUE TO CAPSULE & WATER RESPECTIVELY
(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE (=(DPO/L)+(DP/L)L)
RP: PRESS. RATIO((DP/L)C/(DP/L)L) P: UNIT ENERGY FOR CAPSULE(EQN. 6.18)
M=METER S=SECOND PA=PASCAL W=WATT KG=KILOGRAM

(D.27) PRESS. RATIO & UNIT ENERGY - ALUMINUM CYLINDERS

K= .815 S= 2.7

VAV	VC	RV	(DPO/L)	(DP/L)L	(DP/L)C	RP	P
(M/S)	(M/S)	(-)	(KPA/M)	(KPA/M)	(KPA/M)	(-)	KW-S/KG-M
(L/D= 4)							
1.074	.256	.2384	13.027	.1604	13.1874	82.2157	30.8492
1.699	.986	.5803	13.027	.3948	13.4218	33.9965	11.6062
2.458	1.812	.7372	12.892	.654	13.546	20.7125	9.2214
3.116	2.73	.8761	12.892	1.086	13.978	12.8711	8.0065
3.861	3.716	.9624	12.892	1.604	14.496	9.0374	7.5585
(L/D= 7)							
1.33	.392	.2947	12.795	.1974	12.9924	65.8176	16.5913
1.643	.701	.4267	12.795	.3085	13.1035	42.4749	15.4124
2.012	1.161	.577	12.795	.4689	13.2639	28.2873	11.5353
2.481	1.783	.7187	12.795	.6786	13.4736	19.855	9.4085
2.779	2.163	.7783	12.795	.8637	13.6587	15.8142	6.6049
3.309	2.888	.8728	12.872	1.197	14.069	11.7536	8.0896
(L/D= 10)							
1.756	.714	.4066	13.027	.3578	13.3848	37.4086	16.5197
2.453	1.623	.6616	13.027	.6786	13.7056	20.1969	10.3954
3.171	2.592	.8174	13.027	1.061	14.088	13.278	8.6492
3.972	3.745	.9428	13.027	1.703	14.73	8.6494	5.8801
(L/D= 14)							
1.728	.602	.3484	12.989	.3702	13.3592	36.0864	14.4329
2.503	1.524	.6089	12.989	.6994	13.6884	19.5716	11.2822
3.171	2.527	.7969	12.989	1.111	14.1	12.6913	8.8792
4.049	3.811	.9412	13.182	1.913	15.095	7.8907	8.0463
4.524	4.511	.9971	12.989	2.304	15.293	6.6376	5.7725

(DPO/L) & (DP/L)L: PRESS. GRADIENT DUE TO CAPSULE & WATER RESPECTIVELY
(DP/L)C: TOTAL PRESS. GRADIENT ACROSS CAPSULE (=(DPO/L)+(DP/L)L)
RP: PRESS. RATIO((DP/L)C/(DP/L)L) P: UNIT ENERGY FOR CAPSULE(EQN. 6.18)
M=METER S=SECOND PA=PASCAL W=WATT KG=KILOGRAM

REFERENCES

1. McNown, J. S. and Newlin, J. T., "Drag of Spheres within Cylindrical Boundaries", Proc. 1st. U.S. Nath. Congr. Appl. Mech. Chicago, 801-806, (1951).

2. Young, D. F. "Drag and Lift on Spheres with Cylindrical Tubes", Proc. ASCE, V. 86, 47-57, (1960).

3. Hodgson, G. W. and Charles, M.E., "The Pipeline Flow of Capsules, Part 1: The Concept of Capsule Pipelining", Can. J. Chem. Eng., 41, 43-45, (1963).

4. Charles, M. E., "The Pipeline Flow of Capsules, Part 2: Theoretical Analysis of the Concentric Flow of Cylindrical Forms", Can. J. Chem. Eng., 41, 46-51, (1963).

5. Ellis, H. S., "The Pipeline Flow of Capsules, Part 3: An Experimental Investigation of the Transport by Water of Single Cylindrical Capsules with Density Equal to that of the Water", Can. J. Chem. Eng., 42, 1-8, (1964).

6. Ellis, H. S., "The Pipeline Flow of Capsules, Part 4: An Experimental Investigation of the Transport in Water of Single Cylindrical Capsules with Density Greater than that of the Water", Can. J. Chem. Eng., 42, 69-76, (1964).

7. Ellis, H. S., "The Pipeline Flow of Capsules, Part 5: An Experimental Investigation of the Transport by Water of Single Spherical Capsules with Density Greater than of the Water", Can. J. Chem. Eng., 42, 155-160, (1964).

8. Newton, R., Redberger, P. J. and Round, G. F., "The Pipeline Flow of Capsules, Part 6: Numerical Analysis of Some Variables Determining Free Flow", Can. J. Chem. Eng. 42, 16--173, (1964).

9. Ellis, H. S. and Bolt, L. H., "The Pipeline Flow of Capsules, Part 7: An Experimental Investigation of the Transport by two Oils of Single Cylindrical and Spherical Capsules with Density Equal to that of the Oil", Can. J. Chem. Eng., 42, 201-206, (1964).

10. Round, G. F. and Bolt L. H., "The Pipeline Flow of Capsules, Part 8: An Experimental Investigation of the Transport in Oil of Single Denser than Oil Spherical and Cylindrical Capsules", Can. J. Chem. Eng., 43 (4), 197-205, (1965).

11. Kruyer, J., Redberger, P.J. and Ellis, H. S., "The Pipeline Flow of Capsules, Part 9", J. Fluid Mech., V. 30 (3), 513-531, (1967).

12. Ellis, H. S. and Kruyer, J., "The Pipeline Flow of Capsules, Part 10: Empirical Pressure and Velocity Correlations for Cylindrical Capsules Conveyed in Pipelines up to 4 inches in Diameter", Paper C2, Hydrotransport 1, (1970).

13. Hodgson, G. W., Kruyer, J., Roehl, A. A., Round, G.F., and Ellis, H. S., "Practical Projection of Capsule Pipelining: Edmonton-Hardisty Trunkline Test", J. Can. Petrol. Technology, Jan-Mar., 1-5, (1967).

14. Kennedy, R. J., "Towards an Analysis of Plug Flow Through Pipes", Can. J. Chem. Eng., 44, 354-356, (1966).

15. Figueiredo, O. and Charles, M.E., "Critical Fluid Velocity and Power Requirement for the Startup of a Capsule Pipeline", Can. J. Chem. Eng., 46, 62-65, (1968).

16. Garg, V. K. and Round, G. F., "Capsule Pipeline Flow - a Theoretical Study", Thermodyn. & Fluid Mech. Conv., Inst. of Mech. Eng., London, England, Proceedings 1969-70, 184, 3G(1), pp. 89-100.

17. Round, G. F. and Kruyer, J., "Experiments on the Suspension of Spheres in Inclined Tubes - I, Suspension by Water in Turbulent Flow", Chem. Eng. Sci., Pergamon Press Ltd., Oxford, England, V. 22, 1133-1145 (1967).

18. Round, G. F. and Kruyer, J., "Experiments on the Suspension of Spheres in Inclined Tubes - II, Suspension by Air", Chem. Eng. Sci., V. 29, 397-401, (1974).

19. Tawo, E. N., "An Experimental Study of Incompressible Turbulent Flow in Pipes Containing Sphere Trains", M.Eng. Thesis, McMaster University, (1969).

20. Anzenavs, R. A., "An Experimental Study of the Hydrodynamic Suspension of Spheres and Sphere Trains in a Vertical Pipe Using Water and Polymer Solutions", M.Eng. Thesis, McMaster University, (1973).

21. Latto, B., Round, G. F. and Anzenavs, R., "Drag Coefficients and Pressure Drops for Hydrodynamically Suspended Spheres in a Vertical Tube With and Without Polymer", Can. J. Chem. Eng., 51, 536-541, (1973).

22. Aly, S. L., "The Hydrodynamic Suspension of Sphere and Cylinder Trains in a Vertical Tube Using Water and Polymer Solutions", M.Eng. Thesis, McMaster University, (1974).

23. Lee, S. W., "An Experimental Study of the Hydrodynamic Suspension of Cylinders in a Vertical Pipeline", M.Eng. Thesis, McMaster University, (1974).

24. Latto, B. and Lee, S. W., "The Drag and Pressure Drops for Hydrodynamically Suspended Cylinders in a Vertical Tube With and Without Polymer Addition", Can. J. Chem. Eng. 56, 304-309, (1978).

25. Lazarus, J. H. and Kilner, F. A., "Incipient Motion of Solid Capsules in Pipeline", Hydrotransport 1, Paper C3, Sept. (1970).

26. Jensen, E. J., "Capsule Pipelining - The System and its Potential", Hydrotransport 3, Paper G1, May (1974).

27. Duckworth, R. A. and Singh, G., "An Analytical Treatment of the Flow Through an Annular Channel", Hydrotransport 3, Paper G2, May (1974).

28. Ellis, H. S., "The Effect of the Density of Cylindrical Capsules on the Pressure Gradient in Capsule Pipelines", Hydrotransport 3, Paper G3, May (1974).

29. Lazarus, J. H., "Power Optimization of Hydraulic Transport of Solid Capsules", Hydrotransport 3, Paper G4, May (1974).

30. Kruyer, J., "Friction and Surface Roughness Effects in Capsule Pipelines", Hydrotransport 3, Paper G5, May (1974).

31. Kruyer, J. and Ellis, H. S., "Predicting the Required Liquid Throughput from the Capsule Velocity and Capsule Pressure Gradient in Capsule Pipelines", Can. J. Chem. Eng., 52, 215-221, (1974).

32. Ellis, H. S. and Kruyer, J., "Minimizing the Pressure Gradient in Capsule Pipelines", Can. J. Chem. Eng., 52, 457-462, (1974).

33. Latto, B. and Lai, A., "The Separation Angle for Spheres in a Pipeline", Proceedings of the 4th Biennial Symposium on Turbulence in Liquids, 302-311, (1975).

34. Button, B. L. and Ma, T. H., "Hydraulic Transport of Single Spheres in a Horizontal Pipe", J. Fluid Eng., Trans. ASME, 243-245, (1975).

35. Ellis, H. S., Kruyer, J. and Roehl, A. A., "The Hydrodynamics of Spherical Capsules", Can. J. Chem. Eng., 53, 119-125, (1975).

36. Ellis, H. S., "An Analysis of the Lift-off of Pipeline Capsules", Hydrotransport 4, Paper C1, (1975).

37. Kruyer, J. and White, L. M., "Hydrodynamics of the Design of a Capsule Pipeline", Hydrotransport 4, Paper C2, (1976).

38. Latto, B., Round, G.F. and Aly, S. L., "The Hydrodynamic Suspension of Sphere and Cylinder Trains in a Vertical Tube With and Without Polymer Addition", Hydrotransport 4, Paper C3, May (1976).

39. Lazarus, J. H., "Incipient Power Requirement for Capsule Pipelines", Hydrotransport 4, Paper C4, (1976).

40. Garg, V. K., "Capsule-Pipelining - An Improved Theoretical Analysis", J. Fluid Eng., Transaction ASME, 763-771 (1977).

41. Alnakeeb, H. A. R., "Drag Coefficient for Tethered Spheres in a Vertical Pipeline With and Without Polymer Addition", M.Eng. Thesis, McMaster University, (1977).

42. Van den Kroonenberg, H. H., "A Mathematical Model for Concentric Horizontal Capsule Transport", Can. J. Chem. Eng., 56, 538-543, (1978).

43. Chan, S. and Fung, D., Undergraduate Project Report, McMaster University, April (1979).

44. Streeter, V. L., "Fluid Mechanics", 5th Edition, McGraw-Hill.

45. Richhorn, R. and Small, S., "Experiments on the Lift and Drag of Spheres Suspended in a Poisenille Flow", J. Fluid Mech., V. 20, Pt. 3, 513-527, (1964).

46. White, F. M., "Viscous Fluid Flow", McGraw-Hill, (1974).

47. Schlichting, H., "Boundary-Layer Theory", McGraw-Hill, (1968).

48. "System Design Manual Part 3 - Pipeline Design", Carrier Air Condition Company, Syracuse, New York.