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Empirical evaluation of the eccentric orifice in small diameter pipes

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EMPIRICAL EVALUATION

OF THE ECCENTRIC ORIFICE

IN SMALL DIAMETER PIPES

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A

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ABSTRACT

This investigation has taken different orifice sizes (0.3005", 0.4000", 0.5045", 0.6015") and tested their flow characteristics when used in a 1" diameter pipe. Each orifice was initially placed in a fully eccentric position, that is the circumference of the orifice was placed tangent to the inside circumference of the pipe. Data was taken with the orifice eccentric to concentric in increments of 0.050".

Plots of flow coefficient versus Reynold's number were made for each position of the four orifices tested.

Empirical equations were developed for determining the flow coefficient of the various orifice sizes placed in any eccentric position.

It was also shown that the region near the fully eccentric position was just as stable as the region near the concentric position and is thus very capable of producing accurate flow measurement.

ACKNOWLEDGEMENTS

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Since the author had no previous experience with the computer, a word of thanks is due to Steve Thompson and Robert Peirson who wrote all of his programs.

A special word of thanks to the author's wife who helped him very much by typing this manuscript.

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LIST OF SYMBOLS

d - diameter of the orifice

D - inside diameter of the pipe

e - eccentricity of orifice (in/in)

E - correction term for empirical equations for flow coefficients

$f()$ - step function

g - acceleration due to gravity (ft/sec^2)

g_c - gravitational constant ($lbm - ft/lb_f - sec^2$)

J - mechanical energy equivalent ($778\ ft - lb_f/BTU$)

K - flow coefficient at any specific Reynold's number

K_a - flow coefficient for eccentric orifices

K_e - flow coefficient at $Re/\beta = 10^6 d/15$

K_o - flow coefficient at an infinite Reynold's number

m - mass (lbm)

P - pressure (lb_f/ft^2)

Q - thermal energy (BTU)

Re - Reynold's number of the pipe ($VD\rho/\mu$)

T - temperature ($^{\circ}F$)

u - specifice internal energy (BTU/lbm)

v - specific volume (ft^3/lbm)

V - velocity (ft/sec)

W - work done by the system (BTU)

Z - potential energy (ft)

β - diameter ratio (d/D)

ΔP - differential pressure (psi)

τ - unit of time

I. INTRODUCTION

The orifice, being one of the oldest known devices for measuring or regulating the flow of fluids, has actually been greatly investigated only since the start of the twentieth century. In the last fifty years great strides have been taken towards establishing the thin plate, square-edged, orifice as an accurate flow measuring device. Many investigations have been made, such that the flow coefficients of the orifices tested can be predicted to within a tolerance of about $\pm$ 0.5%.

The work in this field has been mainly with large diameter (4" - 14") pipe with the orifice placed in a concentric position. Little is known about orifices in small diameter pipes (less than 1.6 inches inside diameter).

The question now arises; what if one wants to meter a fluid containing solids in suspension, a toxic, or possibly a highly explosive fluid, where the metering system needs to be completely drained after the system is shut down?

One answer would be an eccentric orifice, that is an orifice whose circumference would coincide, at a point, with the circumference of the pipe in which it was installed. If the orifice was placed in the lowest possible position in the pipe the system could be completely drained when shut down, without entrapping any fluid. At present, this type of orifice installation needs to be calibrated after being installed.

If the orifice was positioned somewhere other than concentric or fully eccentric what would the flow coefficient be? Since theory can not predict the flow coefficient for any orifice in any position, there is a need for empirical relationships calibrating these positions.

The author believes that there has never been an attempt made at developing an empirical relationship for determining the flow coefficient of an orifice placed at different positions in a small diameter pipe. Casale[1*] has shown that it was feasible to use an eccentric orifice in a small diameter pipe.

It is the intent of this thesis to fill a small part of the gap in calibration needed when an orifice, used in a small diameter pipe, is positioned at some position other than concentric.

*Superscripts used in this manner are references to the bibliography.

II. REVIEW OF LITERATURE

The greatest source of error in the primary measuring elements is probably the possible deviation from the specification that the upstream edge of the orifice plate be square and sharp. A slight, almost imperceptible, rounding of the orifice edge can produce a considerable increase in the discharge coefficient, which results in low flow measurement. This is especially true with the smaller orifices in the smaller line sizes, since the effect of the edge imperfection is relative. A wire-edge burr, or fin, on the orifice edge is also undesirable since it can alter the flow pattern of the stream from that corresponding to proper measurement.[2]

Tyson[3] states that when metering water the usual test for sharpness of a square-edged orifice is to pull the thumbnail across the edge. If it is sharp enough to use it will remove a shaving from the nail.

The thickness of the orifice plate at the orifice edge shall not exceed:[2]

1. 1/50 of the pipe diameter (D)
2. 1/8 of the orifice diameter (d)
3. 1/4 of the dam height, $(\frac{D-d}{2})$

the minimum of these requirements governing in all cases.

In some cases the orifice plate thickness will be greater than the limitations stated above. When this occurs the downstream edge should be beveled at 45° or less to the face of the plate leaving the thickness within the requirements.[2]

For concentric orifices, the orifice must be centered to within 3% of the inside diameter of the pipe.[2]

Generally there are three types of pressure tap locations for measuring the pressure loss through an orifice. They are as follows:

1. Flange taps - located on the flanges to hold the orifice plate in the pipe. The center of the upstream tap hole should be one inch from the upstream face of the orifice plate and the center of the downstream tap hole should be one inch from the downstream face.

2. Pipe taps - the center of the upstream tap is 2 1/2 pipe diameters from the plate and the center of the downstream tap is located 8 pipe diameters from the plate.

3. Vena contracta taps - center of taps are located at one pipe diameter from the plate on the upstream side and at the point of minimum pressure on the downstream side.

If any serious distortion of the flow occurs there will be inaccuracy in the results obtained from the orifice. Recommendations have therefore been made concerning diameter ratio ($\beta = d/D$) and minimum lengths of straight pipe required before and after an orifice, depending upon the installation.[2] When the diameter of the orifice may require changing, the length of straight pipe installed should be that corresponding to the highest diameter ratio used. Graphs have been drawn plotting minimum lengths of straight pipe required versus diameter ratio. When the diameter ratio is .6 the upstream length of straight pipe must be at least 13 pipe diameters after an elbow, tee, or cross, but with the installation of a globe or regulating valve, the upstream distance is increased to 31 diameters. In either case the downstream requirement is only 5 diameters. The straight run requirements become less as the diameter ratio decreases.

Straight run requirements may also be shortened by the installation of straightening vanes. Certain specifications must be met in the construction of the vanes. The diameter of any passage through the vanes shall not exceed one-fourth (1/4) the inside diameter of the pipe. the cross-sectional area of any passage between the vane tubes shall not exceed one-sixteenth (1/16) the cross-sectional area of the containing pipe. The length of the vanes shall be at least ten (10) times the inside diameter of the vane tubes.[4]

There are also limitations on the diameter ratios possible. Kirk[5] recommends ratios from .2 to .6 as providing best accuracy. If the diameter ratio is too small the pressure loss becomes too great, and if the ratio is too large the differential pressure reading ($\triangle P$) becomes unstable and too small to detect.

In 1935 the ASME[4] assembled and published many investigations on concentric orifices in pipes. This work brought about some empirical equations relating flow coefficient to orifice diameter, pipe diameter, and Reynold's number. The equations for orifice installations using flange taps are as follows:

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + 530/D^{1/2}),$$

$$\begin{aligned} K_e &= 0.5993 + 0.007/D + (0.364 + 0.076/D^{1/2})\beta^4 \\ &+ 0.4(1.6 - 1/D)^5 \ (0.07 + 0.5/D - \beta)^{5/2} \\ &- (0.009 + 0.034/D) \ (0.5 - \beta)^{3/2} \\ &+ (65/D^2 + 3) \ (\beta - 0.7)^{5/2}, \end{aligned}$$

where K_e is the flow coefficient for Re (pipe Reynold's number) = $10^6 d\beta/15$. The flow coefficient as Re approaches infinity is given by

$$K_o = K_e \left[(10^6 d)/(10^6 d + 15E)\right].$$

Thus the flow coefficient at any Re is given by

$$K = K_o \left[1 + E/(Re/\beta)\right] .$$

These equations provide flow coefficients within a tolerance of $\pm$ 1.5 percent.

Although these equations are not to be used for pipe diameters of less than 1.6 inches they provide an excellent starting point for developing empirical relations in small diameter pipes.

As the temperature of the water changes, its density and viscosity also change. Using values of density of water at 70°F and 80°F from tables by Holman[6] it can be shown that the percent deviation of $\sqrt{\rho}$ over this 10 degree range is 0.063 percent.

The viscosity of water decreases as the temperature increases. Diehl[2] stated that tests conducted for the determination of discharge coefficients when measuring water and viscous fluids have indicated that the factor for viscosity varies with pipe diameter, orifice diameter, differential pressure and specific gravity, as well as absolute viscosity. These tests indicate that the factor for viscosity approaches a maximum value and then decreases. Consequently, it is very necessary to correct the measurement for the effect of the viscosity at flowing conditions.

In his paper on Fluid Flow Measurements, Benedict,[7] gave a cubic equation developed for the determination of the dynamic viscosity of water from 32°F to 120°F as a function of temperature. It is as follows: $\mu = (21.35768 - 0.38108\ T + 0.3058 \times 10^{-2}T^{2} - 0.924598 \times 10^{-5}T^{3})10^{-4}$.

III. APPARATUS

The basic apparatus used was the same as that built by Casale[1], however, there were changes and additions; so a brief description of the system's components will follow. All discussion pertains to the schematic diagram in Figure 1.

The centrifugal pump used was an Aurora, with double impeller and was capable of pumping 12.5 GPM of water against a back pressure of up to 150 psi. The maximum flow obtainable through the test section was approximately 24 GPM. The pump was supplied by a tank with a capacity of approximately 100 gallons. A valved by-pass was installed across the pump. One inch piping was used throughout with the exception of the by-pass which was three-quarter inch pipe. The main control valve was a Jenkins one inch globe valve.

An upstream pressure gage was installed mainly for monitoring purposes.

The temperature well contained a mercury in glass thermometer capable of being read to 1°F.

The flow straightener used by Casale was replaced by a straight section of pipe of over 40 diameters length. The flow straightener was shorter than that required by the codes,[4] and the total cross-sectional area capable of passing fluid was small compared to that of the pipe. It was felt that since space was not a consideration, the long length of straight pipe would produce far less turbulence than the flow straightener.

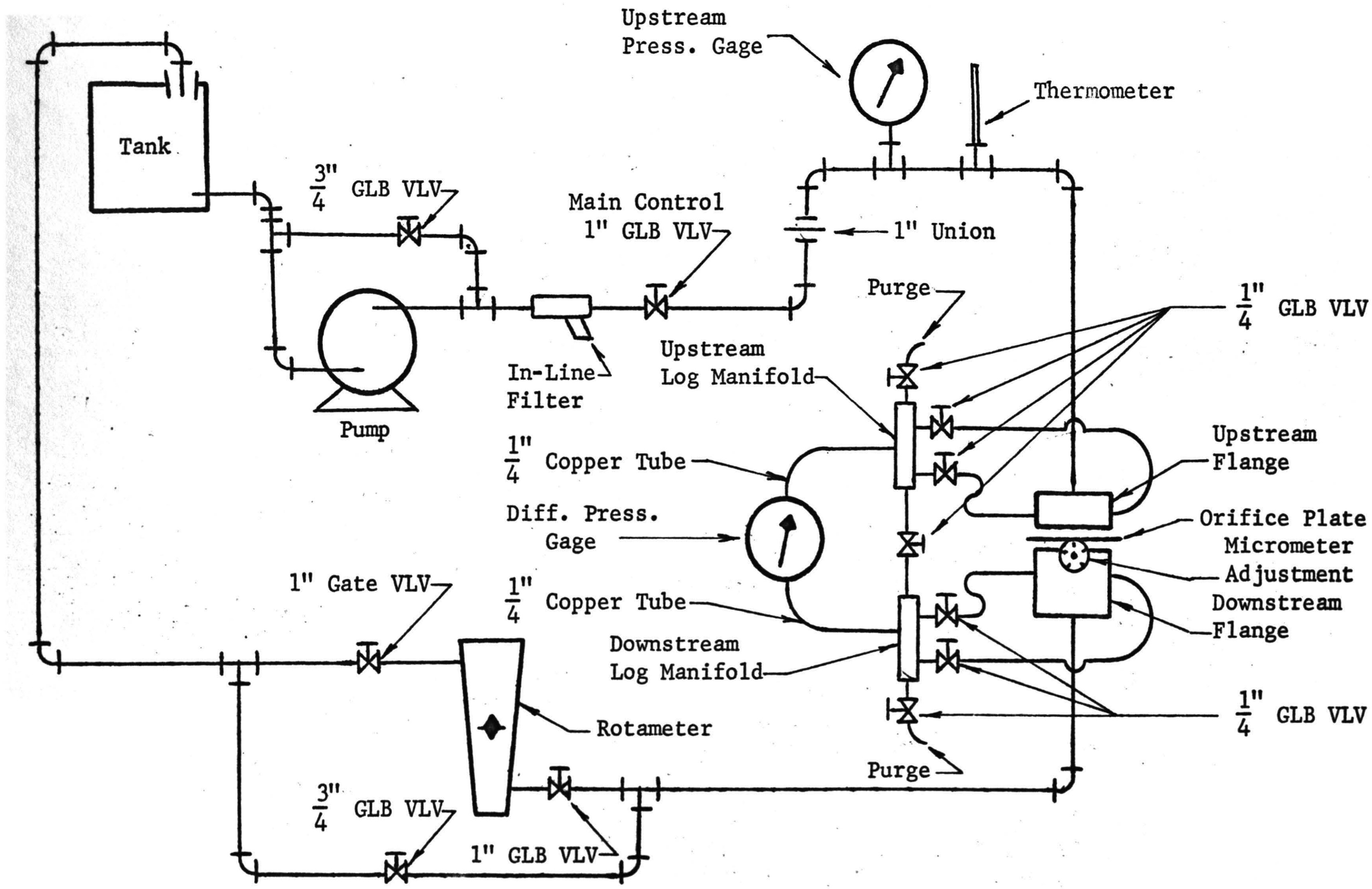

Figure 1. Schematic of Apparatus Used in Investigation

The bore of the total test section containing the flanges was exactly one inch.

All the pressure taps used by Casale to try to find the vena contracta, with the exception of the top and bottom sets of flange taps were plugged. If the orifice position is to be changed, even slightly, the use of vena contracta taps would be very impractical.

Both top and bottom taps on the upstream side were connected to a log manifold by copper tubing and a valve. The manifold was connected to the high pressure connection of the differential pressure gage. The same manifolding procedure was used on the downstream taps and this manifold was connected to the low pressure connection of the differential pressure gage. This method of manifolding enabled readings to be made using the top taps only, the bottom taps only, or both.

The two manifolds were connected by a valved line enabling the differential pressure gage to be by-passed when the system was started. Each manifold had a valve and line vented to the atmosphere to permit the system to be purged of entrapped air.

The differential pressure gage used was an Ashcraft double bourdon tube gage graduated in 1 psi increments from 0 to $\pm$ 50 psi. With this gage the differential pressure could be read accurately to within 1/2 psi and estimated to 1/4 psi. The gage was calibrated with a dead weight tester on the high pressure connection and atmospheric pressure on the low pressure connections. (See Figure 2).

To eliminate parallax in reading the differential pressure gage a sight was constructed from a section of four inch aluminum pipe and one-fourth inch aluminum plate. The sight fit the face of the gage and made all readings very consistent. (See Figure 4.)

The four orifice plates built by Casale were used after they were slightly altered. The downstream face was beveled at a 45° angle leaving the thickness of the plate at the orifice 0.010 inch. Each orifice was then measured on the three diameters and the measurements were averaged. These values (0.3005", 0.4000", 0.5045", 0.6015") were used in all calculations. Each plate was slotted so as to permit it to be moved vertically, colinearly with a line drawn between the top and bottom taps, from a fully eccentric position to a concentric position.

A device was constructed to raise the orifice plate known finite amounts. (See Figure 5.) It consisted of a structural member attached to the downstream flange, a holder for the orifice plate, and a micrometer adjustment. The micrometer adjustment consisted of a screw with 20 threads per inch and a dial graduated every 72° and marked 1 through 5 on its circumference. Turning the dial through one mark raised the orifice 0.010 inch. The orifice, which was initially placed in the fully eccentric position, could thus be moved accurately to any position in the pipe.

The downstream face of the orifice plate was followed by over 20 diameters of straight pipe.

Connected to the downstream section of pipe was a Fisher and Porter series 1700 Standard Enclosed Flowrator Meter mounted in a typical horizontal line installation. A valved by-pass was used to protect the rotameter when starting the system. (See Figure 4.)

The outlet of the rotameter was at a higher elevation than that of the orifice. This elevation insured that the test section would always be filled with water. By using this set up the need for a downstream control valve was eliminated, which eliminated the possibilities of over controlling, which might cause erroneous readings.

The rotameter, which was graduated in percent of maximum flow (26.5 GPM), could be estimated to the nearest 1/4 percent. Before any runs were made the rotameter was calibrated by setting a flow rate and collecting the water in a weigh barrel. (See Figure 3.) The time to collect 100 pounds of water was recorded for each setting. From this data a flow rate could be calculated and compared to that read from the rotameter.

The water leaving the rotameter was piped back to the tank supplying the pump. By recirculating the water a constant level was kept in the tank, thus maintaining a constant suction head on the pump.

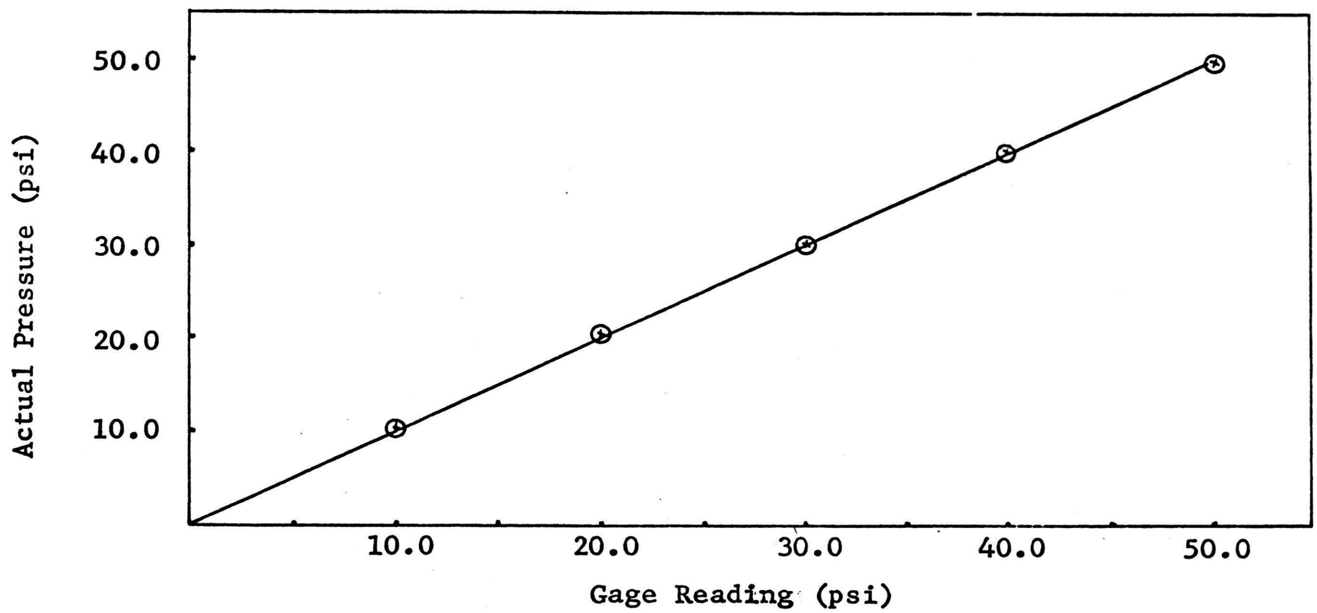

Figure 2. Differential Pressure Gage Calibration Curve

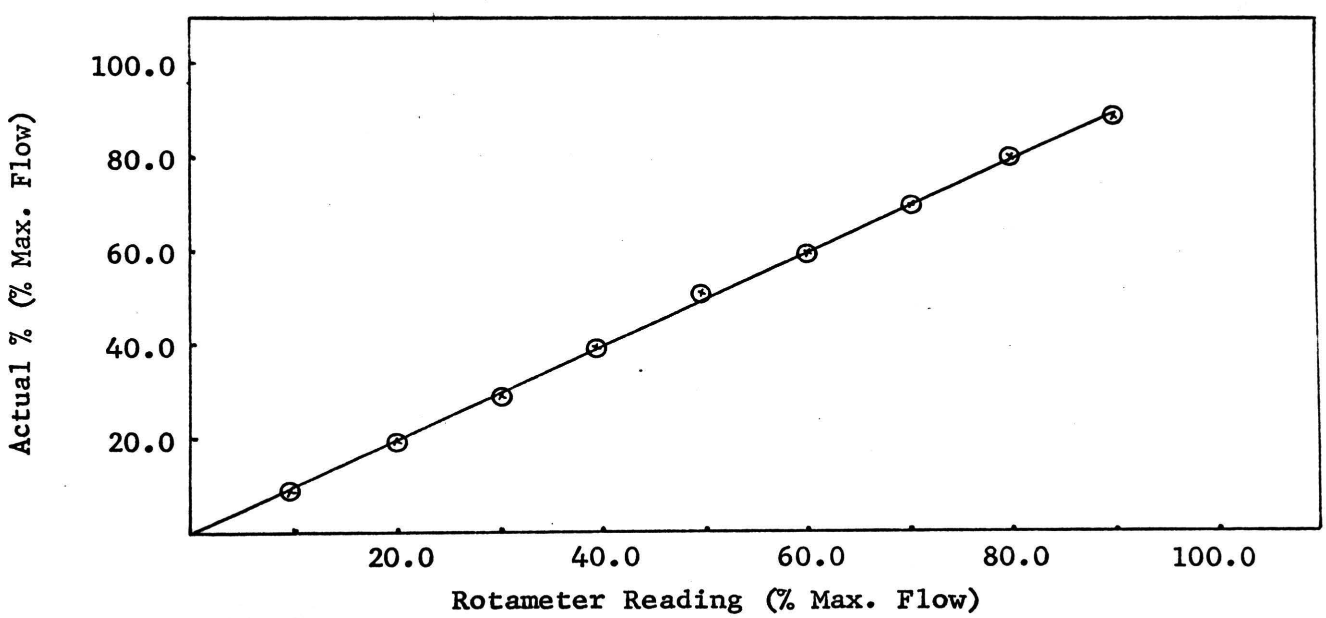

Figure 3. Rotameter Calibration Curve

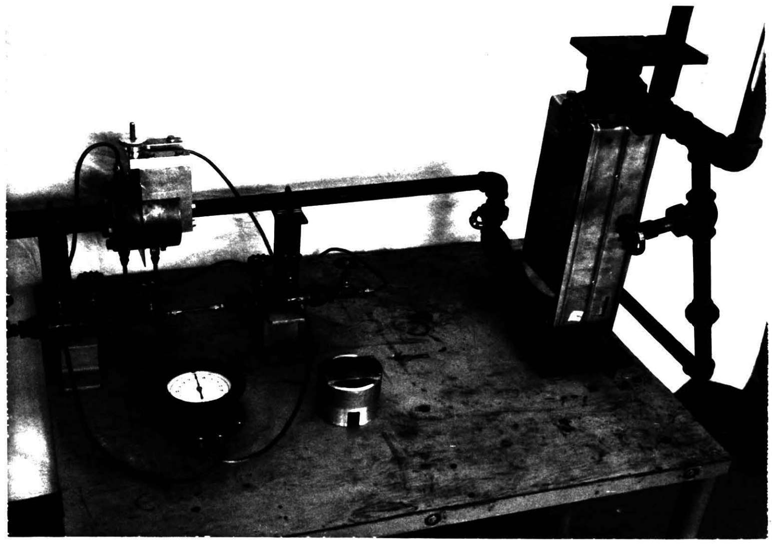

Figure 4. Apparatus

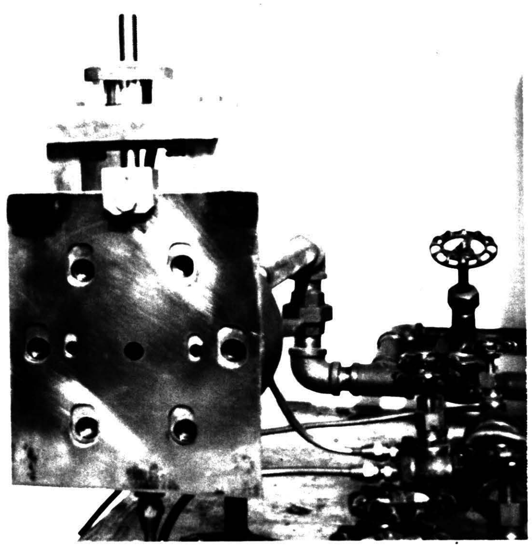

Figure 5. Orifice Plate and Micrometer Adjustment

IV. PROCEDURE FOR TAKING DATA

To obtain a good cross-section of the best possible range of diameter ratios for the most accurate results, four orifice sizes were used in the one inch test section (0.3005", 0.4000", 0.5045", 0.6015"). The procedure for taking data was the same for each orifice size.

With the flanges separated the orifice was attached to the micrometer adjustment and positioned such that the circumference of the bottom edge of the orifice was tangent to the bottom inside edge of the pipe. The flanges were then bolted together.

After the tank was filled to a certain level the pump was started with the by-pass valve opened and the main control valve closed. The flow could be adjusted to any desired value (zero flow to maximum possible flow) by simultaneously opening the main control valve and closing the by-pass valve. The by-passes of both the differential pressure gage and the rotameter were initially opened to prevent damage to the instruments. After the system was purged of entrapped air the by-passes on both the differential pressure gage and the rotameter were closed.

The flow was adjusted until a given pressure drop across the orifice was reached. These adjustments varied with orifice size and were as follows:

For the 0.3005" and 0.4000" orifices the differential pressure gage was read from 0 to 50 psi adjusting the flow to read every 2 psi. For the 0.5045" orifice the differential pressure was read from 0 to 20 psi adjusting the flow to read every 1 psi. At slightly over 20 psi (ΔP) the maximum flow rate through the system was attained.

For the 0.6015" orifice the differential pressure was read from 0 to 11.5 psi adjusting the flow to read every 0.5 psi. Again as with the 0.5045" orifice the maximum flow rate was attained.

After each flow adjustment the upstream pressure was checked, the ΔP was recorded, and the temperature and rotameter readings were read and recorded.

Normally both top and bottom taps were open. It was felt that there was a need to standardize the method of taking differential pressure readings, since the orifice position was to be changed in the pipe. Occasionally readings with only the top taps open were compared against those with both top and bottom taps open. The same procedure was followed using the bottom taps only.

With the orifice in the eccentric positions, reading ΔP with only the top set of flange taps open gave a higher ΔP than the reading with both sets of taps open, and reading ΔP with only the bottom set of flange taps open gave a lower value of ΔP than with both sets of taps open. In the concentric positions all readings were the same regardless of which set of taps were used. By always reading both taps an average ΔP was obtained.

All runs were made with the water temperature between 75° and 85°F. Since the water was recirculated its temperature rose during the runs. After each run the system was flushed and cooler water was added to maintain the temperature within the stated range.

While flushing the system the flanges were loosened and the orifice plate was moved up 0.050". The same procedure was then followed until a concentric position was reached.

V. CORRELATION OF DATA

Writing the first law of thermodynamics for an open system,

$$\frac{\delta Q}{d\tau} + \frac{\delta m_1}{d\tau}\left(\frac{u_1}{J} + \frac{P_1 v_1}{J} + \frac{V_1^2}{2Jg_c} + \frac{Z_1 g}{Jg_c}\right) = \frac{\delta W}{d\tau} + \frac{\delta m_2}{d\tau}\left(\frac{u_2}{J} + \frac{P_2 v_2}{J} + \frac{V_2^2}{2Jg_c} + \frac{Z_2 g}{Jg_c}\right)$$

$$+ \frac{d}{d\tau}\left(\frac{mu}{J} + \frac{mV^2}{2Jg_c} + \frac{mZg}{Jg_c}\right)_{stored},$$

where (1) represents the energy entering the system and (2) represents the energy leaving the system. Many terms in the above equation were dropped for the following reasons:

(1) The energy stored for any given length of time is zero since the system is at steady state.

(2) The heat transfer rate is zero since there is no heat added to or rejected from the system.

(3) There is no work done on or by the orifice.

(4) The internal energy entering and leaving the orifice is the same since the temperature is constant.

(5) The difference of potential energy across the orifice is zero.

Rewriting the first law for the orifice gives:

$$\frac{\delta m_1}{d\tau}\left[\frac{P_1 v_1}{J} + \frac{V_1^2}{2Jg_c}\right] = \frac{\delta m_2}{d\tau}\left[\frac{P_2 v_2}{J} + \frac{V_2^2}{2Jg_c}\right] .$$

The flow rate into the system equals the flow rate out of the system, therefore,

$$\frac{P_1 v_1}{J} - \frac{P_2 v_2}{J} = \frac{V_2^2}{2Jg_c} - \frac{V_1^2}{2Jg_c} .$$

Since the velocity is inversely proportional to the cross-sectional area of flow:

$$\frac{P_1v_1}{J} - \frac{P_2v_2}{J} = \frac{V_2^{\,2}}{2Jg_c}\left[1 - \frac{A_2^{\,2}}{A_1^{\,2}}\right].$$

Solving for $V_2^{\,2}$

$$V_2^{\,2} = \frac{2g_c(P_1v_1 - P_2v_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}$$

$v_1 = v_2 = \frac{1}{\rho}$ which remains constant because the temperature of the fluid entering and leaving the orifice is the same.

$$\frac{A_2}{A_1} = \frac{d^2}{D^2} = \beta^2.$$

Solving for V_2 gives

$$V_2 = \left[\frac{2g_c(P_1 - P_2)}{\rho(1-\beta^4)}\right]^{1/2}.$$

The theoretical mass flow rate is written as:

$$\dot{m} = \rho_2A_2V_2 = \rho A_2 \left[\frac{1}{(1 - \beta^4)}\right]^{1/2} \left[\frac{2g_c(P_1 - P_2)}{\rho}\right]^{1/2},$$

which may be written as

$$A_2\left[\frac{1}{1 - \beta^4}\right]^{1/2} \left[(2g_c\rho\Delta P)\right]^{1/2}, \text{ where } \Delta P = (P_1 - P_2).$$

Since the actual flow rate is always less than theoretical the coefficient of discharge is defined, as:

$$C_d = \frac{\dot{m}\text{ actual}}{\dot{m}\text{ theoretical}}.$$

Now, the actual flow rate may be written as:

$$\dot{m}_{\text{actual}} = \frac{A_2C_d}{(1 - \beta^4)^{1/2}}(2g_c\rho\Delta P)^{1/2}.$$ When

$$\left[\frac{1}{1 - \beta^4}\right]^{1/2},$$

defined as the approach factor, is combined with the coefficient of discharge the flow coefficient is obtained.

$$K = \frac{C_d}{\left[1 - \beta^4\right]^{1/2}}$$

and the actual flow may be written as

$$\dot{m}_{actual} = A_2 K (2 g_c \rho \Delta P)^{1/2}.$$

Since all runs were made at an average water temperature of 80°F, no temperature deviation ever exceeded 5°F, the density may be considered constant.

Reading ΔP in psi, and making the equation dimensionally correct give

$$\dot{m}_{actual} = A_2 K \sqrt{2 g_c \rho}\, \sqrt{\Delta P} = A_2 K \left[\frac{2(32.16)(62.19)}{144}\right]^{1/2} \sqrt{\Delta P}$$

$$= A_2 K\ (5.270) \sqrt{\Delta P}\ .$$

Solving for K gives

$$K = \frac{\dot{m}_{actual}}{5.270\ A_2 \sqrt{\Delta P}} = \frac{\dot{m}_{actual}}{5.270\ \frac{\pi d^2}{4} \sqrt{\Delta P}} = \frac{\dot{m}_{actual}}{4.139\ d^2 \sqrt{\Delta P}}\ .$$

Reynold's number of the pipe may be written

$$Re = \frac{V_1 D_1 \rho_1}{\mu_1}\ .$$

Multiplying numerator and denominator by A_1 gives

$$Re = \frac{\rho_1 A_1 V_1 D_1}{\mu A_1} = \frac{\dot{m}}{\mu \pi \frac{D}{4}} = \frac{4\dot{m}}{\pi D \mu}\ .$$

Making the equation dimensionaless yields

$$Re = \frac{48\ \dot{m}}{\pi D \mu} .$$

Using an empirical relation for μ to compensate for temperature change

$$Re = \frac{48\ \dot{m}}{\pi D(21.35768 - 0.38108\ T + 0.3058 \times 10^{-2} T^2 - 0.924598 \times 10^{-5} T^3) 10^{-4}} .$$

Since the inside diameter of the pipe is 1.0 inch,

$$Re = \frac{48\ \dot{m}}{\pi(21.35768 - 0.38108\ T + 0.3058 \times 10^{-2} T^2 - 0.924598 \times 10^{-5} T^3) 10^{-4}} .$$

The above equations were used to calculate flow coefficients and Reynold's numbers for all the data taken. Since the equations are quite long, it would have been time consuming to calculate all the data by hand. The computer was therefore used for nearly all calculations.

A curve of flow coefficient versus Reynold's number was plotted for each set of data (each different position gave a different set of data). This produced a graph similar in shape to that developed by Tuve[14]. (See Figure 6). Due to the low values of Reynold's numbers required it would be difficult to obtain many points in Region A with the type of apparatus used in this study. The points in Region A were eliminated from all subsequent programs.

Since flow coefficient was plotted versus pipe Reynold's number, Region B was varied in length depending upon the diameter ratio. The curves could be normalized in the independent variable direction by plotting flow coefficient versus Reynold's number/beta. The points plotted in region B appeared to be well suited to curve fitting by the method of least squares.

The following procedure was used four times, once for each diameter ratio used in the tests. For clarity, the entire procedure will be described using only the curves for the 0.4000" diameter orifice. The curves for the other orifices may be found in Appendices A, B, and C.

Designations were made as to independent and dependent variables (Reynold's number/beta and flow coefficient respectively), and the least squares method was used for each curve. Since it was not known which degree approximations would be best, second, third and fourth order approximations were determined. After viewing these results it was clearly evident that the second order approximation was best. This curve of flow coefficient versus Reynold's number/beta was then plotted through the data points. (See Figures 8-14.)

The orifice position in the pipe will be referred to as its eccentricity (e), which is defined as the distance the orifice is moved from concentric position divided by the total possible movement of the orifice. (See Figure 7.) Thus, for all orifices e = 0 for the concentric position, and e = 1.0 for the fully eccentric position.

For each curve plotted, an average value of flow coefficient was calculated. Care was taken to average each curve over the same range of Reynold's numbers/beta (0.80×10^5 to 0.16×10^6). The average values of flow coefficients were then plotted versus the eccentricity of the orifice. (See Figure 15.) Each point on this graph then represented an average value of the curves shown in Figures 8-14 corresponding to its respective eccentric position.

The horizontal line extending from e = 0 to e = 0.10 represents three percent of the inside diameter of the pipe converted to the eccentricity of the orifice by the relation ($\frac{.06D}{D-d}$).

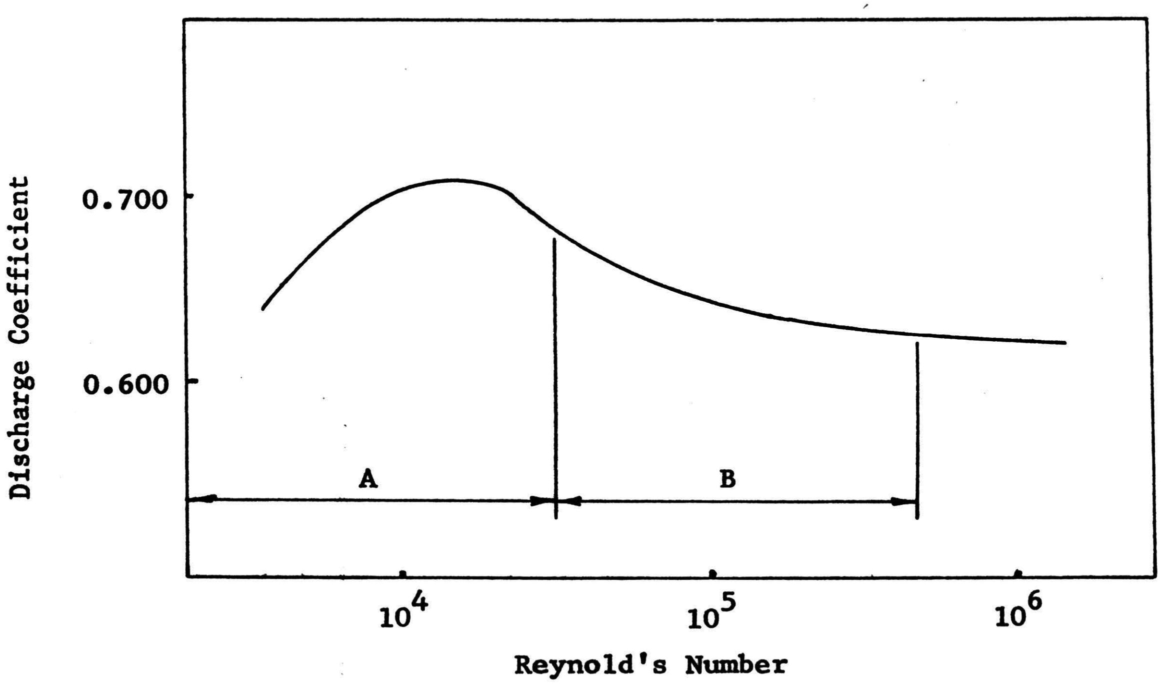

Figure 6. Typical Curve Showing Discharge Coefficient For Concentric Orifices (By Tuve[14])

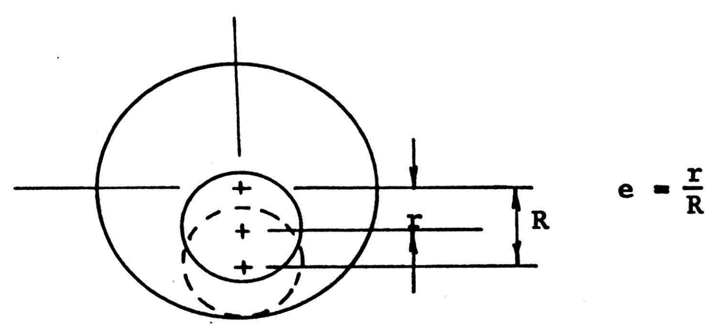

Figure 7. Eccentricity

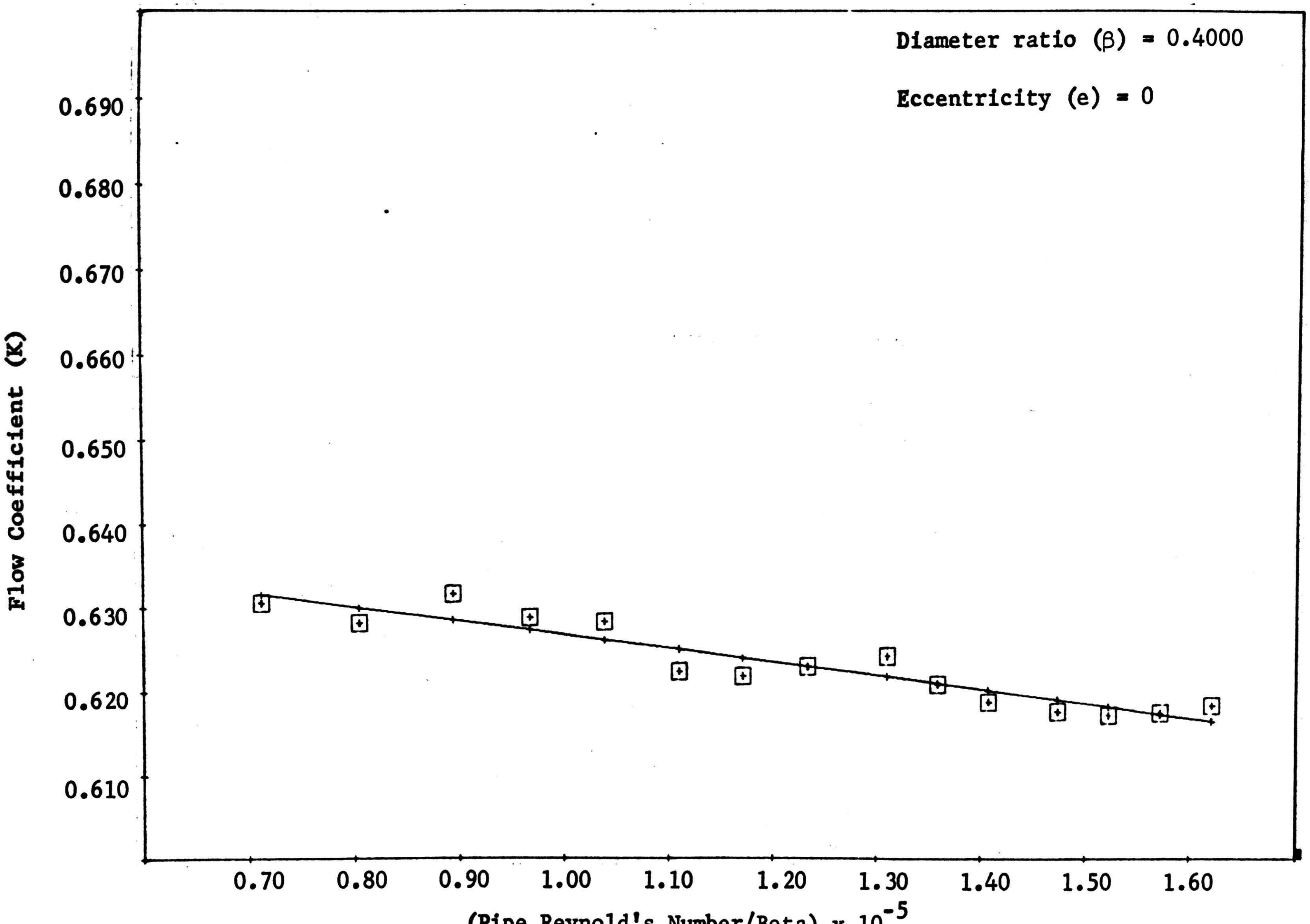

Figure 8. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

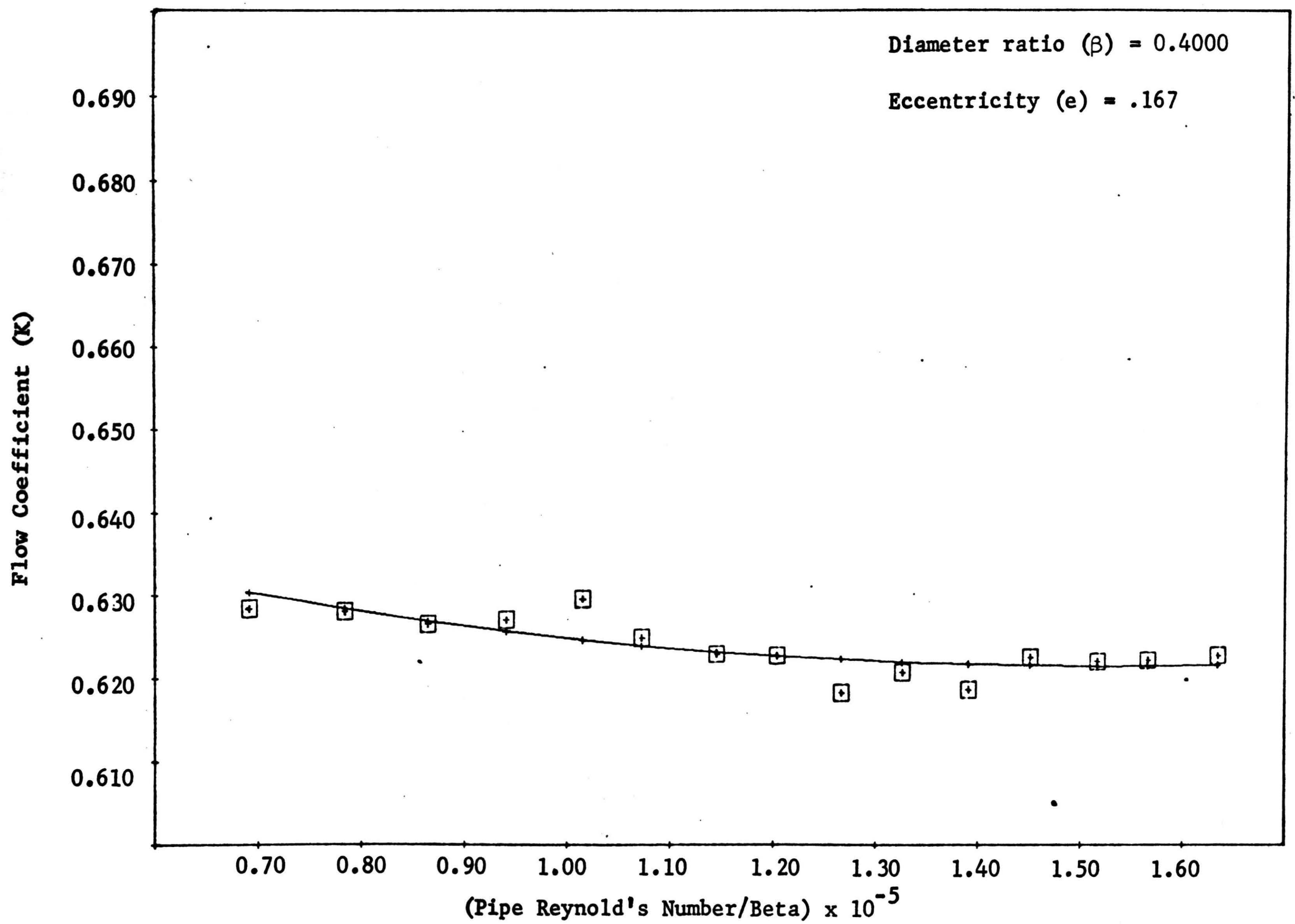

Figure 9. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

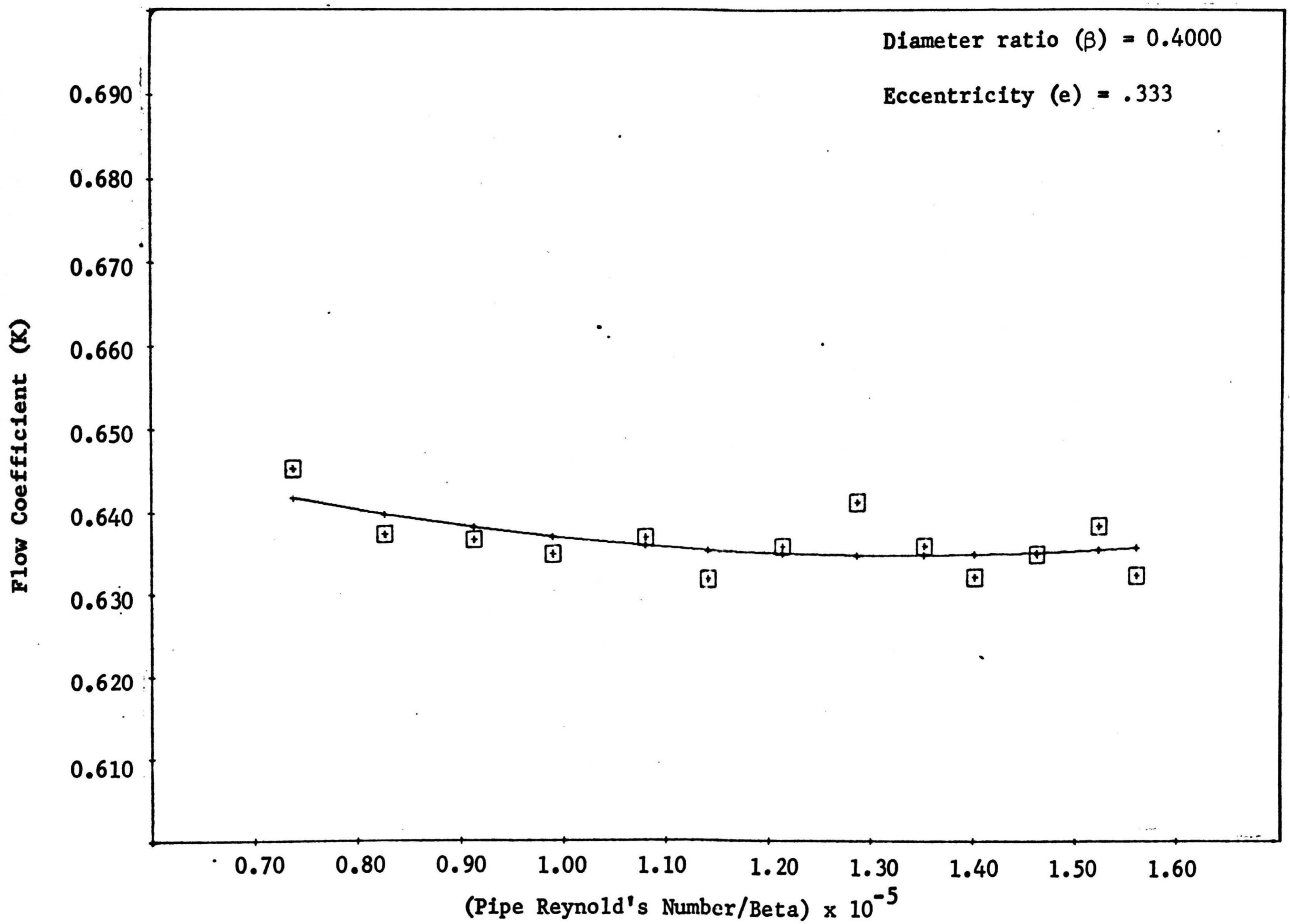

Figure 10. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

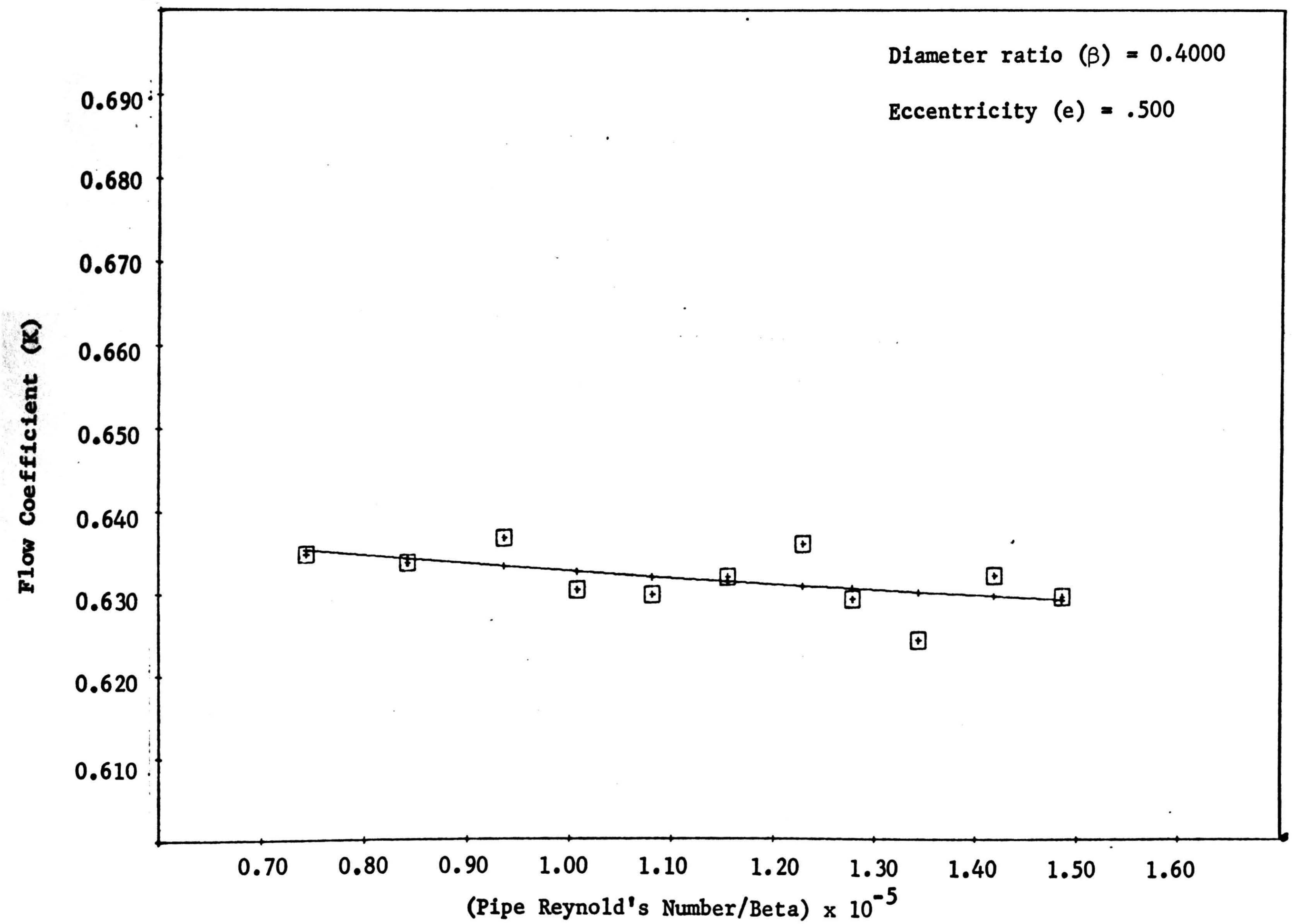

Figure 11. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

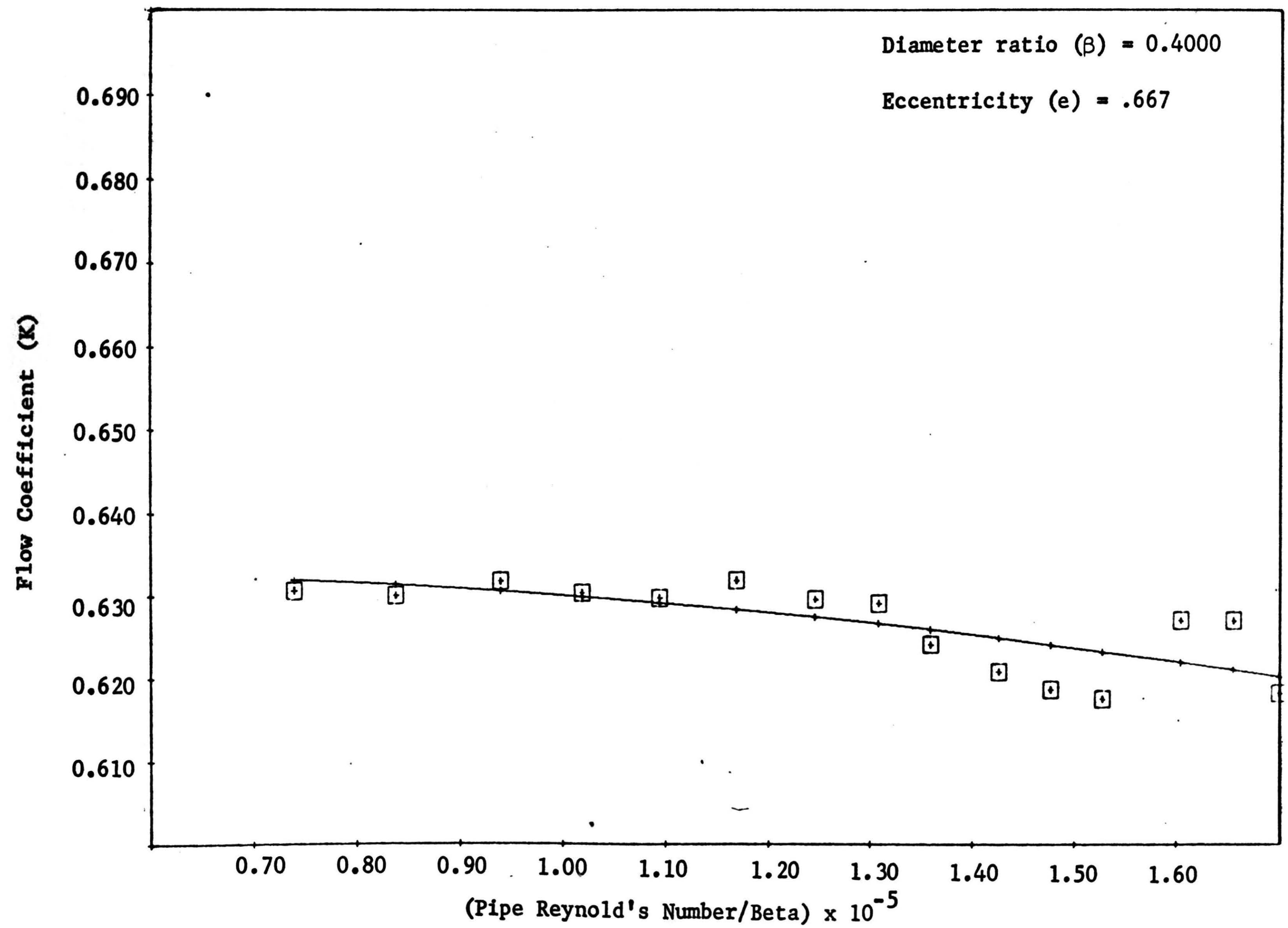

Figure 12. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

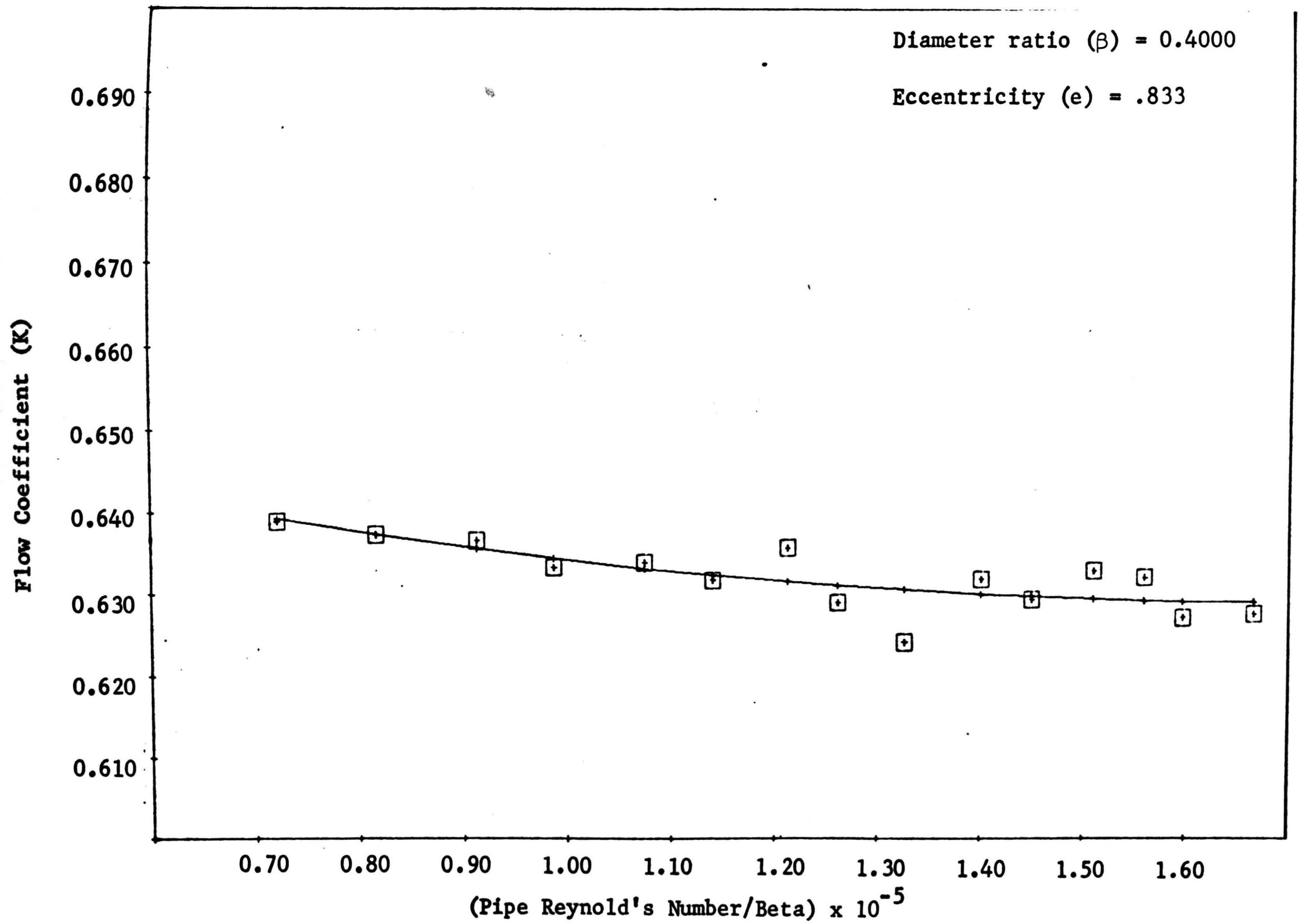

Figure 13. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

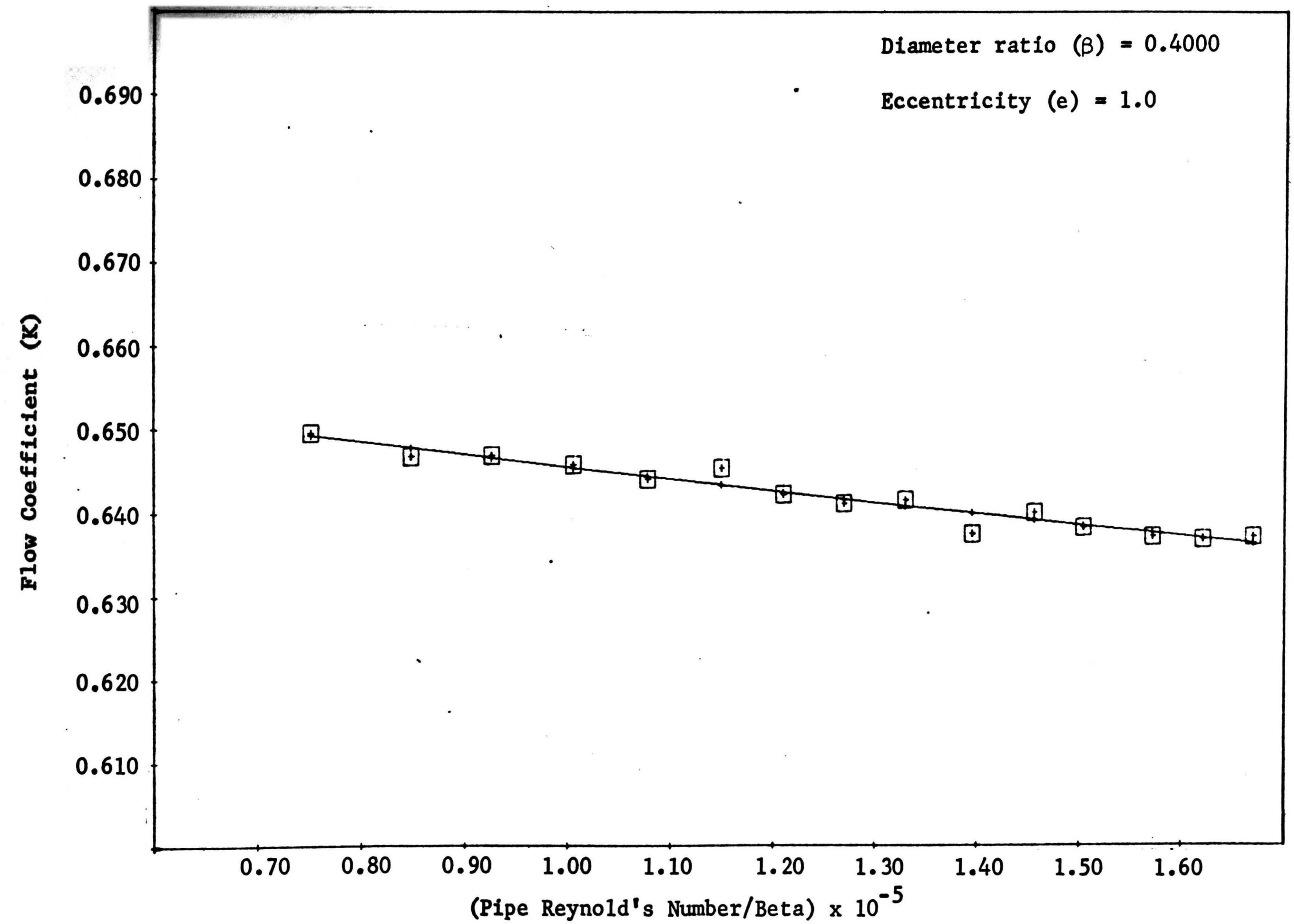

Figure 14. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

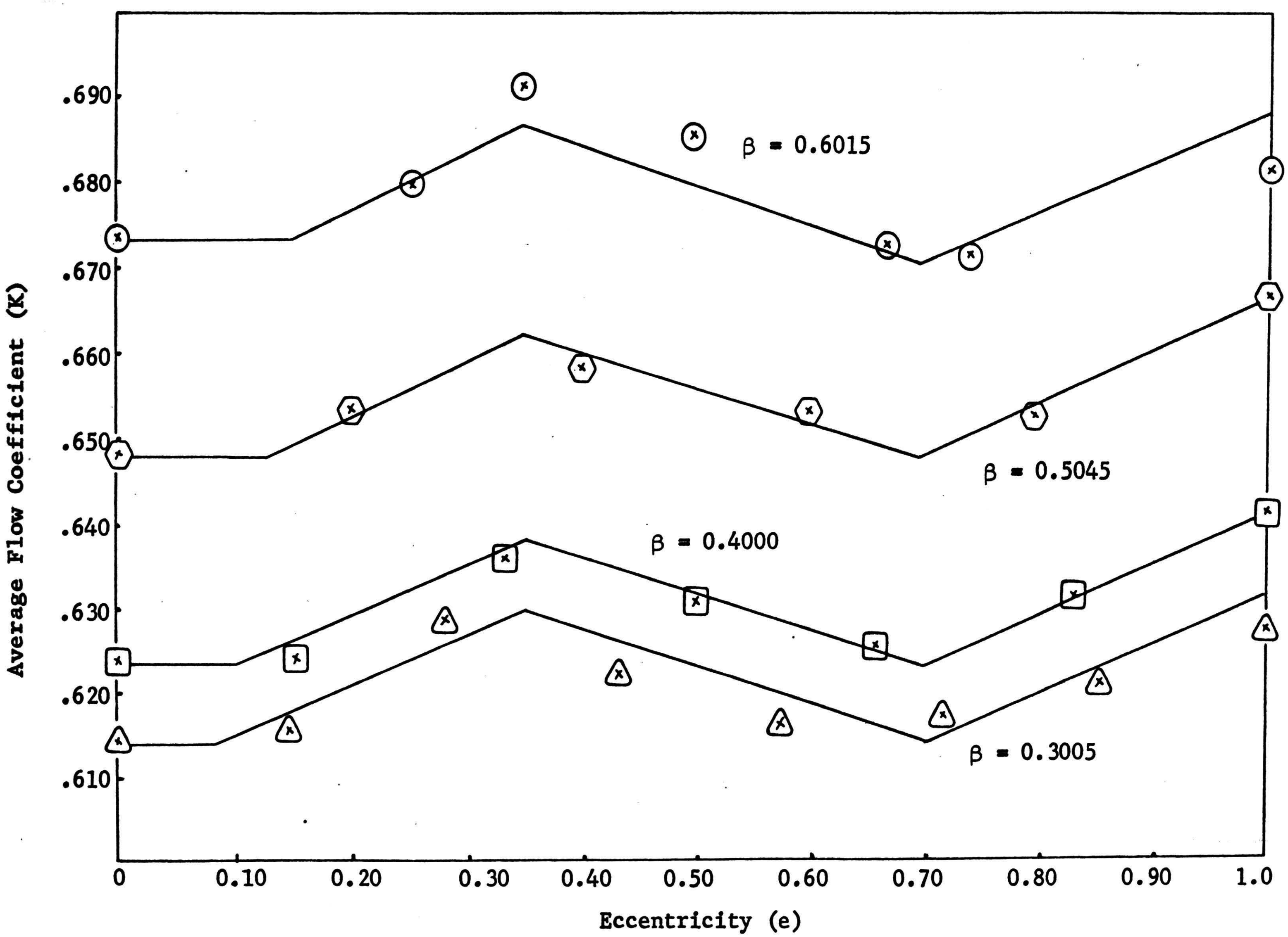

Figure 15. Average Values of Flow Coefficient Versus Eccentricity For All Diameter Ratios Tested

This curve is by no means linear and at first glance it appears that there is no justification for the straight line portions drawn. When this curve is plotted on an expanded scale and viewed along side the similar curves of the other three orifices (see Figure 15), it becomes evident that the portions of the curve between $e = 0$ to $e = .35$ and $e = .70$ to $e = 1.0$ may be quite accurately approximated by a straight line with a slope of $0.06396 \frac{K}{e}$. The center portion is approximated by a straight line having a slope of $-0.04715 \frac{K}{e}$.

If a relationship were known relating the flow coefficient to the diameter ratio, the flow coefficient could be calculated for any orifice, in any position in the pipe. To obtain this relationship the curves of flow coefficient versus Reynold's number/beta for the concentric position of each orifice were compared to the curves given by the ASME empirical equations for larger diameter pipes. Approximately five deviations of the experimental curves from the ASME curves[4] were taken for each orifice within the same range of Reynold's number/beta (0.80×10^5 to 0.16×10^6). The actual data curves ranged from 1.25 percent to 3.34 percent higher than the ASME equations. All the deviations were averaged; the average being 2.17 percent.

The equations for calculating the flow coefficients of concentric, square-edged orifices in a 1" diameter line may now be written as:

$$E = d(830 - 5000\beta + 9000\beta^2 - 4200\beta^3 + 530/D^{1/2}),$$

$$\begin{aligned} K_e = {} & 1.0217 \left[0.5993 + 0.007/D + (0.364 + 0.076/D^{1/2})\beta^4\right] \\ & + 1.0217 \left[0.4(1.6 - 1/D)^5 (0.07 + 0.5/D - \beta)^{5/2}\right] \\ & - 1.0217 \left[(0.009 + 0.034/D)(0.5 - \beta)^{3/2}\right] \\ & + 1.0217 \left[(65/D^2 + 3)(\beta - 0.7)^{5/2}\right], \text{ and} \end{aligned}$$

$K_o = K_e\ (10^6 d)/(10^6 d + 15E)$, and $K = K_o(1 + E/(Re/\beta))$, where K_e represents the flow coefficient for Re/β of $10^6 d/15$, and K_o is the limiting value of flow coefficient when Reynold's number approaches infinity. If $(0.07 + 0.5/D - \beta)^{5/2}$, $(0.5 - \beta)^{3/2}$ or $(\beta - 0.7)^{5/2}$ becomes negative, the term containing this negative quantity is defined as zero.

The values from the concentric curves may be shifted to calculate the flow coefficient at various values of eccentricity by the following relations:

$$K_a = K\left[1 + f(e - \frac{.06D}{D-d})\right] \qquad 0 \leq e \leq .35,$$

$$K_a = K\left[1 + f(.70 - e)(0.04715)\right] \qquad .35 \leq e \leq .70,$$

and $$K_a = K\left[1 + f(e - .70)(0.06396)\right] \qquad .70 \leq e \leq 1.0;$$

where K_a represents the flow coefficient of an eccentric orifice. The first correction factor applies in the region of $e = 0$ to $e = .35$, where $f(e - \frac{.06D}{D-d})$ is defined as:

zero when $e < (\frac{.06D}{D-d})$,

and $(e - \frac{.06D}{D-d})$ when $\frac{.06D}{D-d}) \leq e \leq .35$.

The second correction factor applies in a region of $e = .35$ to $e = .70$, where $f(.70 - e)$ is defined as:

zero when $0 \leq e < .35$ and $.70 < e \leq 1.0$

and $.70 - e$ when $.35 \leq e \leq .70$.

The third correction factor applies in the region of $e = .70$ to $e = 1.0$, where $f(e - .70)$ is defined as:

zero when $e < .70$,

and $e - .70$ when $.70 \leq e \leq 1.0$.

The curves shown in Figure 16 represent values of flow coefficients for the concentrically positioned orifices given by the equations just stated. Applying the correction factors for eccentricity merely shifts the curve upward a given amount depending upon the amount of eccentricity. All resulting curves are parallel.

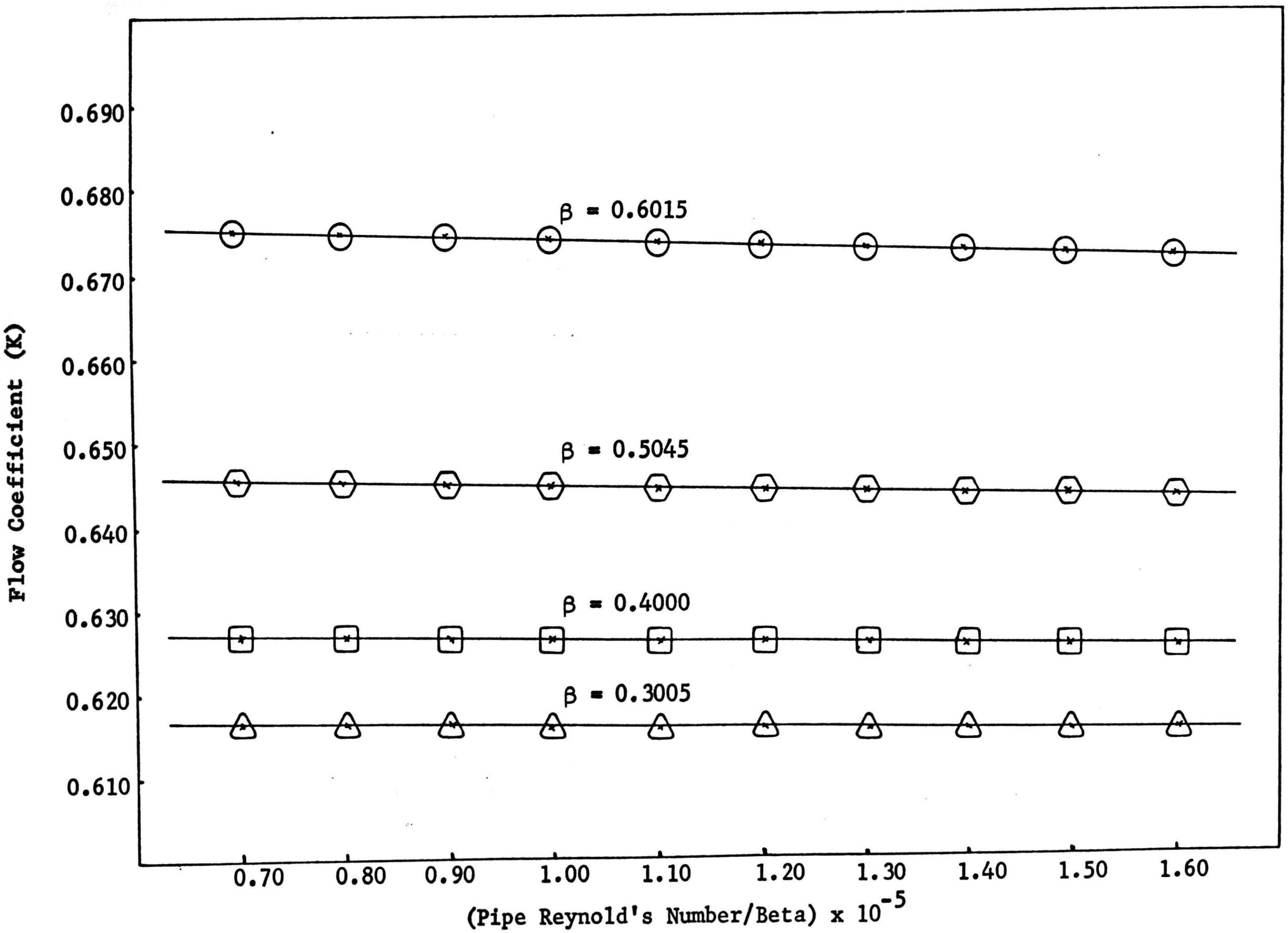

Figure 16. Curves from Empirical Equations For Concentric Orifices in a 1" Diameter Line

VI. CONCLUSIONS AND RECOMMENDATIONS

Water was used as the test fluid simply as a matter of convenience and safety. This correlation will theoretically apply to any Newtonian fluid since the flow coefficient is plotted versus Reynold's number/beta, which are all dimensionless terms.

As stated earlier there is a need for stating the exact method of placing the flange taps. Changing the orifice position only slightly would effect the pressure reading if only one set of taps was used. The use of two sets of taps manifolded together does not change the effect produced by moving the orifice, however, if the taps are located colinearly with the direction of travel of the orifice an average ΔP is always read.

While recording the data it was noticed that the ΔP readings were very erratic in the region $.35 < e < .70$. As the orifice was moved from the fully eccentric position the dam height $(\frac{D-d}{2})$ increased. This greatly changed the path of the water and extreme turbulence was generated. In some instances the turbulence was actually audible. As the orifice was moved upward near the concentric position stability, was again restored. For this reason the author feels that the data in this region may be less reliable than in the other regions.

When the values of flow coefficients obtained from the empirical relationships were compared with those taken from the curves obtained by experimental data it was noted that the maximum deviation of the curves from the empirical equations was $\pm$ 1.8 percent. Each curve drawn was within this tolerance.

The author believes that the empirical equations derived from this study will apply to all orifices, in any position in a 1" diameter pipe, having a diameter ratio of .3 to .6. It is also believed that these equations will apply for any value of Reynold's number in the pipe. Since the equations are empirical and there is no true justification for the last two statements, one must be content to state the observed tolerance over the range tested.

It is evident that there is a need for investigation through a higher range of Reynold's number. Several pumps would have to be run in parallel or a larger pump must be used to obtain a larger flow rate. With a larger flow rate a larger orifice, possibly a .7 inch diameter orifice, could be tested quite successfully. The larger flow rate would also create turbulence problems in the smaller orifices. The differential pressure gage would have to be damped to eliminate erratic fluctuations. The measuring instruments, such as the differential pressure gage and rotameter, would have to be much larger, however accuracy must not be sacrificed for size. Accuracy is of the utmost importance in the observation of data. If the differential pressure gage was larger and damped sufficiently, a smaller orifice, possibly of .2 inch diameter, may be tried.

Correlating could be attempted in a larger, and in a smaller diameter pipe to see if the same correlation holds for all pipes under 1.6 inches inside diameter, or whether a different correlation is needed for each.

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APPENDIX A

Curves of experimental data for a 0.3005" diameter orifice in a 1" diameter line.

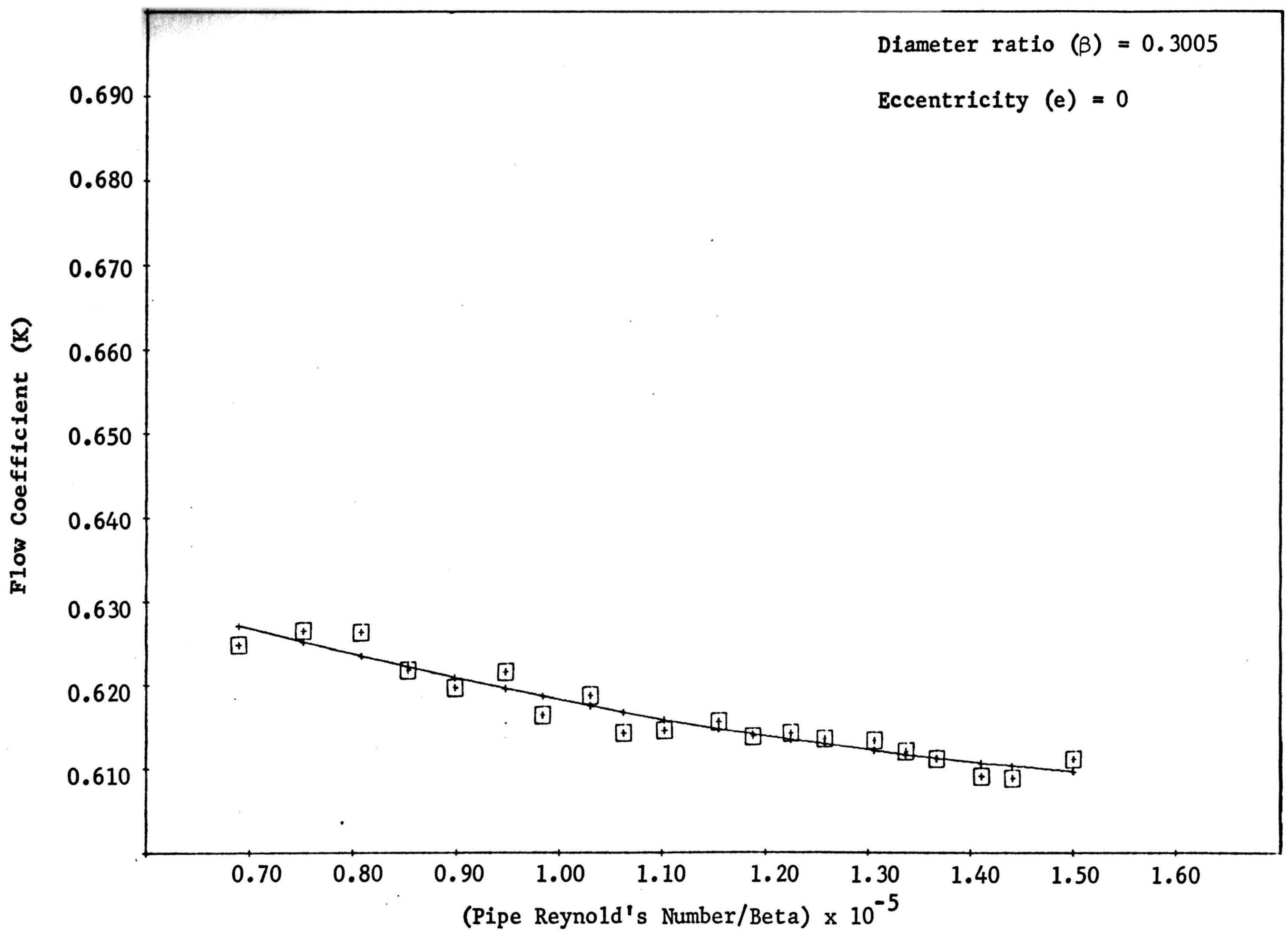

Figure 17. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

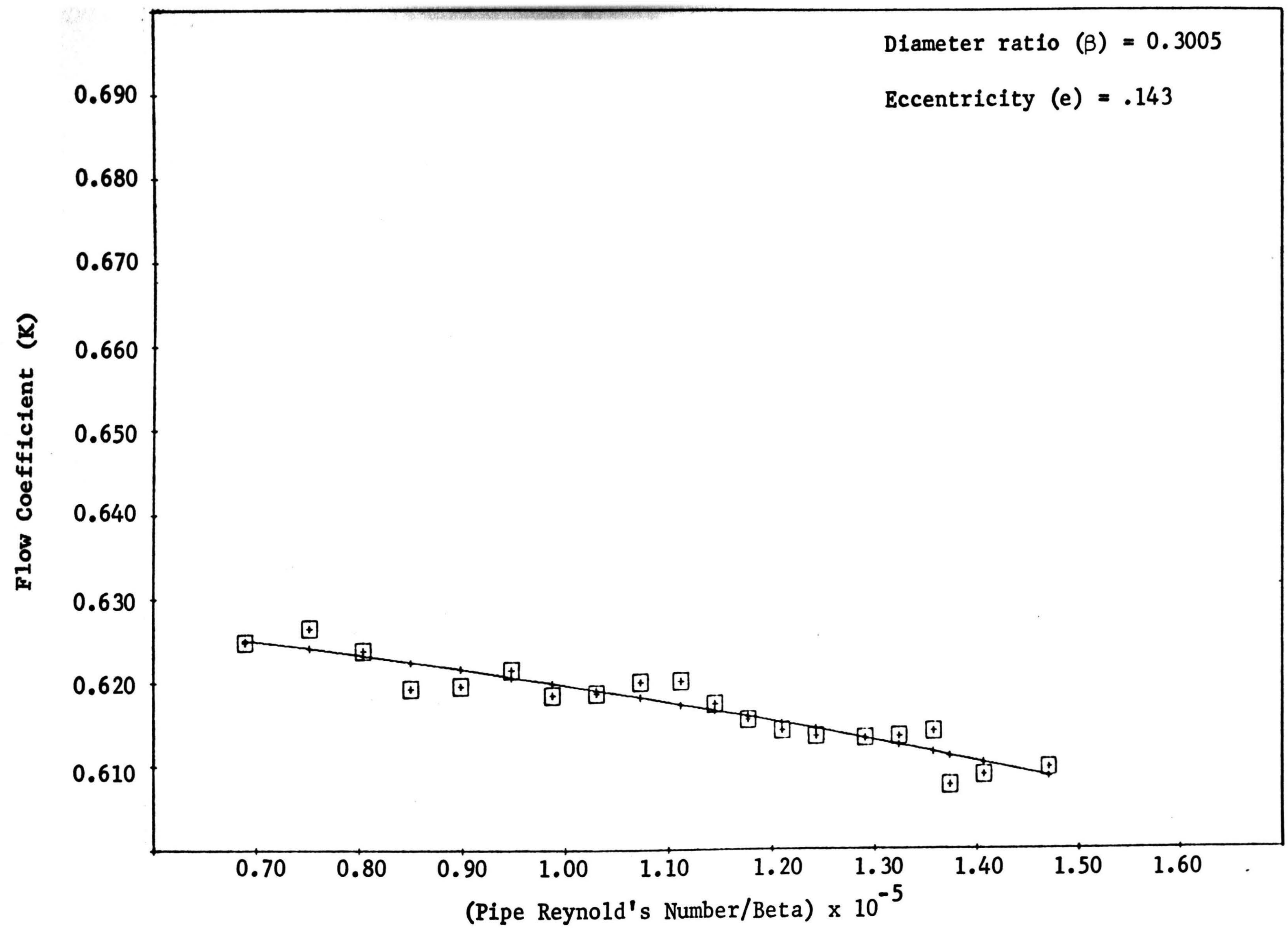

Figure 18. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

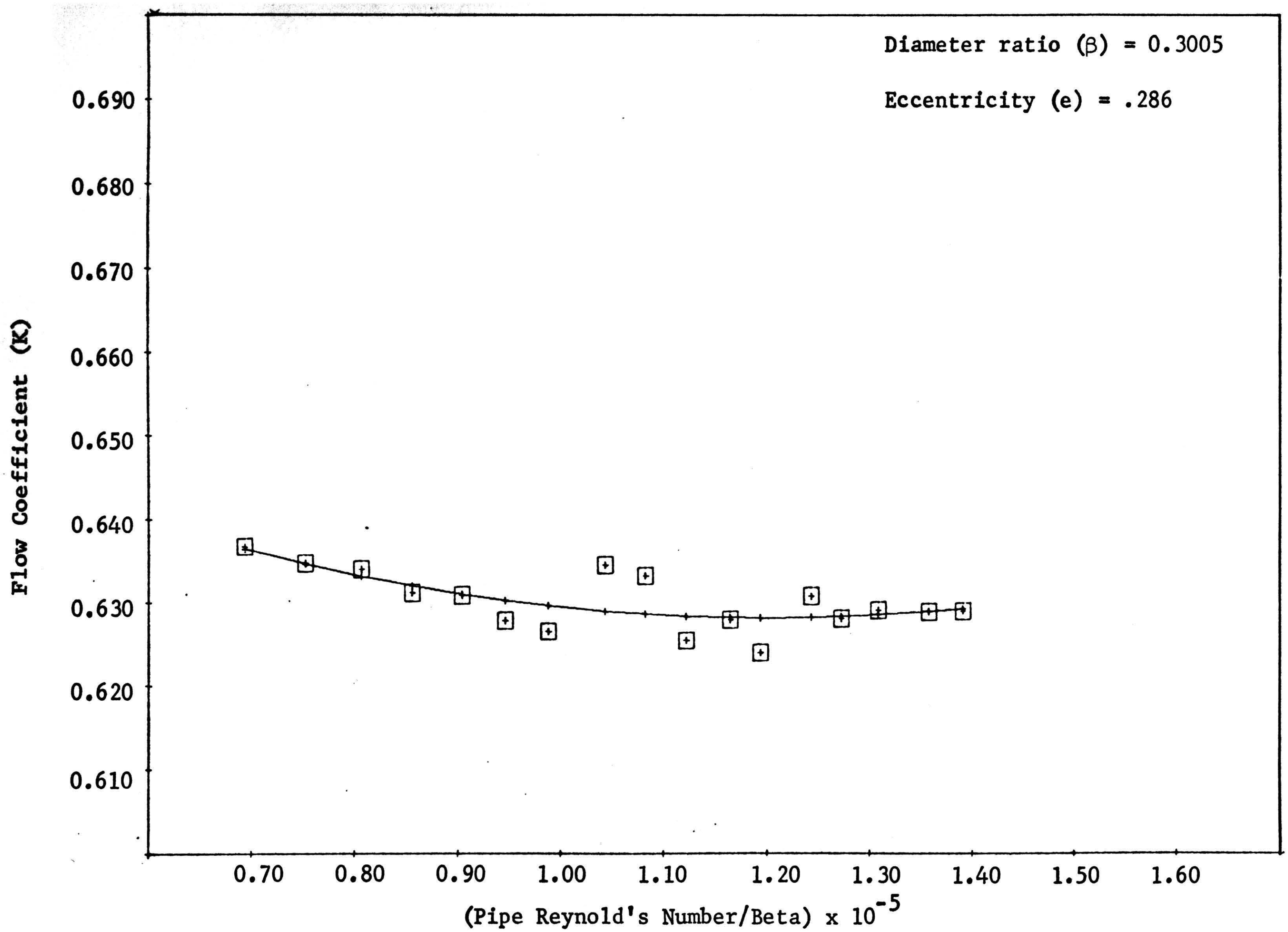

Figure 19. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

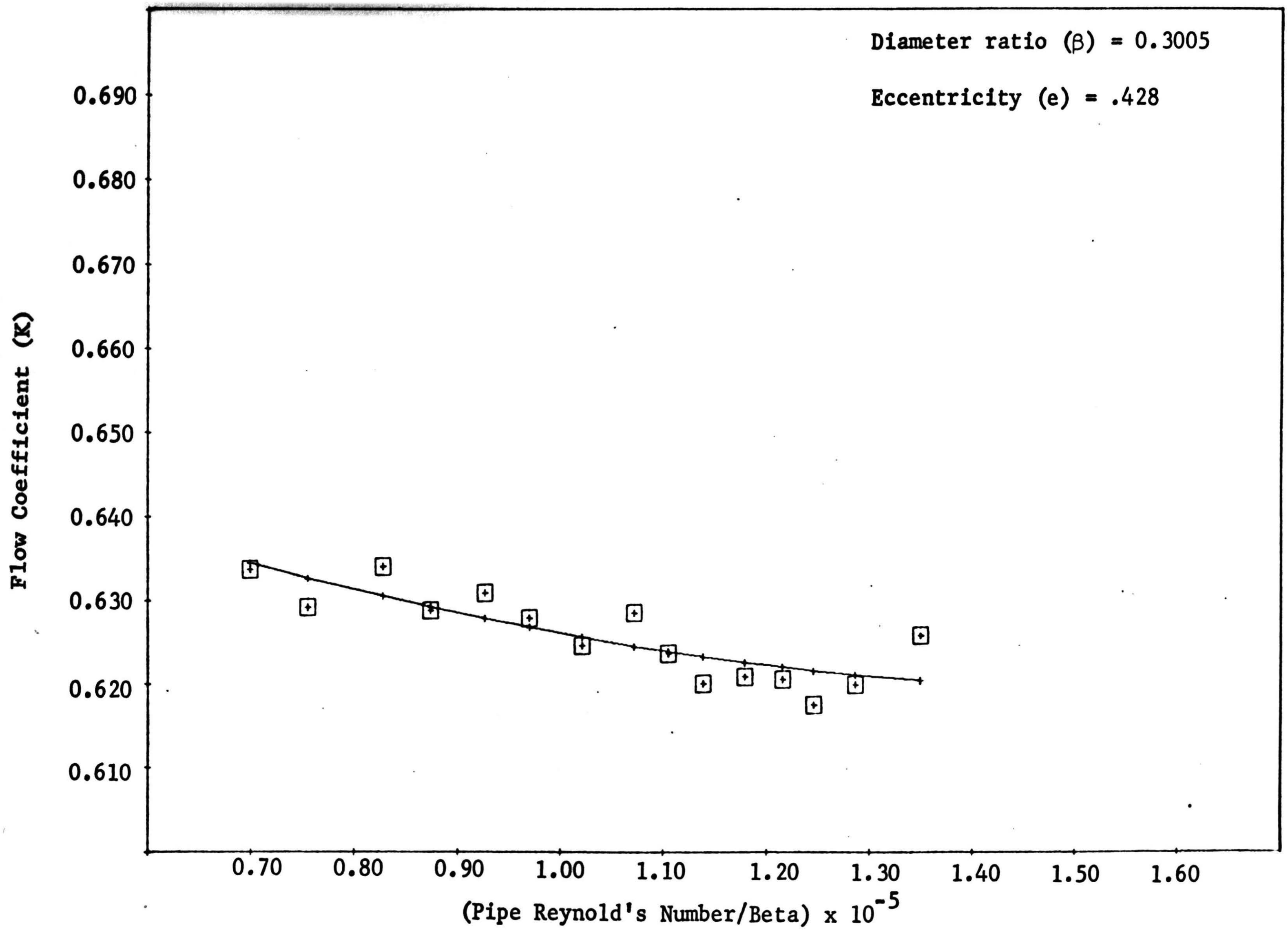

Figure 20. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

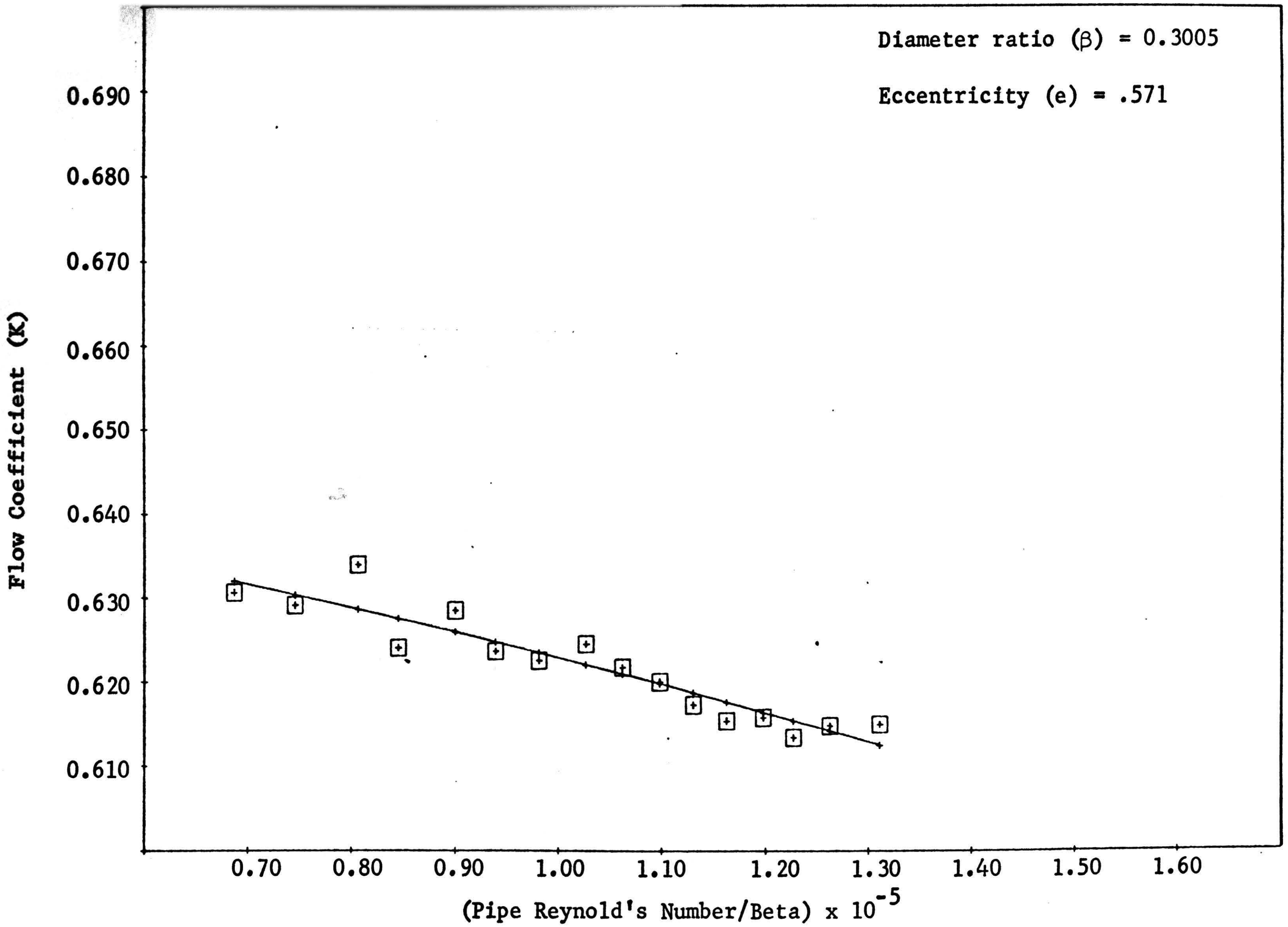

Figure 21. Flow Coefficients Versus Reynold's Number/Beta
For a Square-Edged Orifice in a 1" Diameter Line

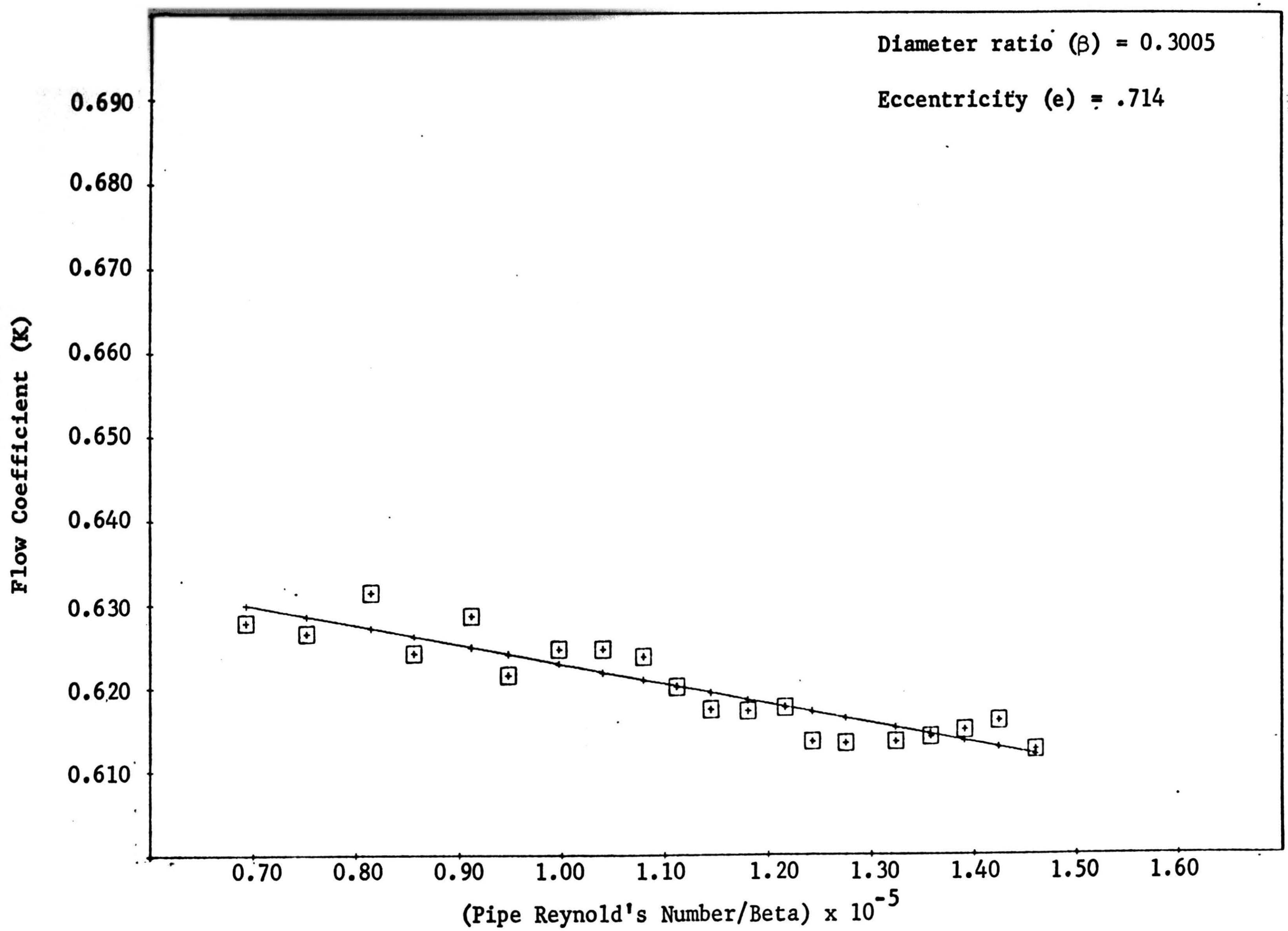

Figure 22. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

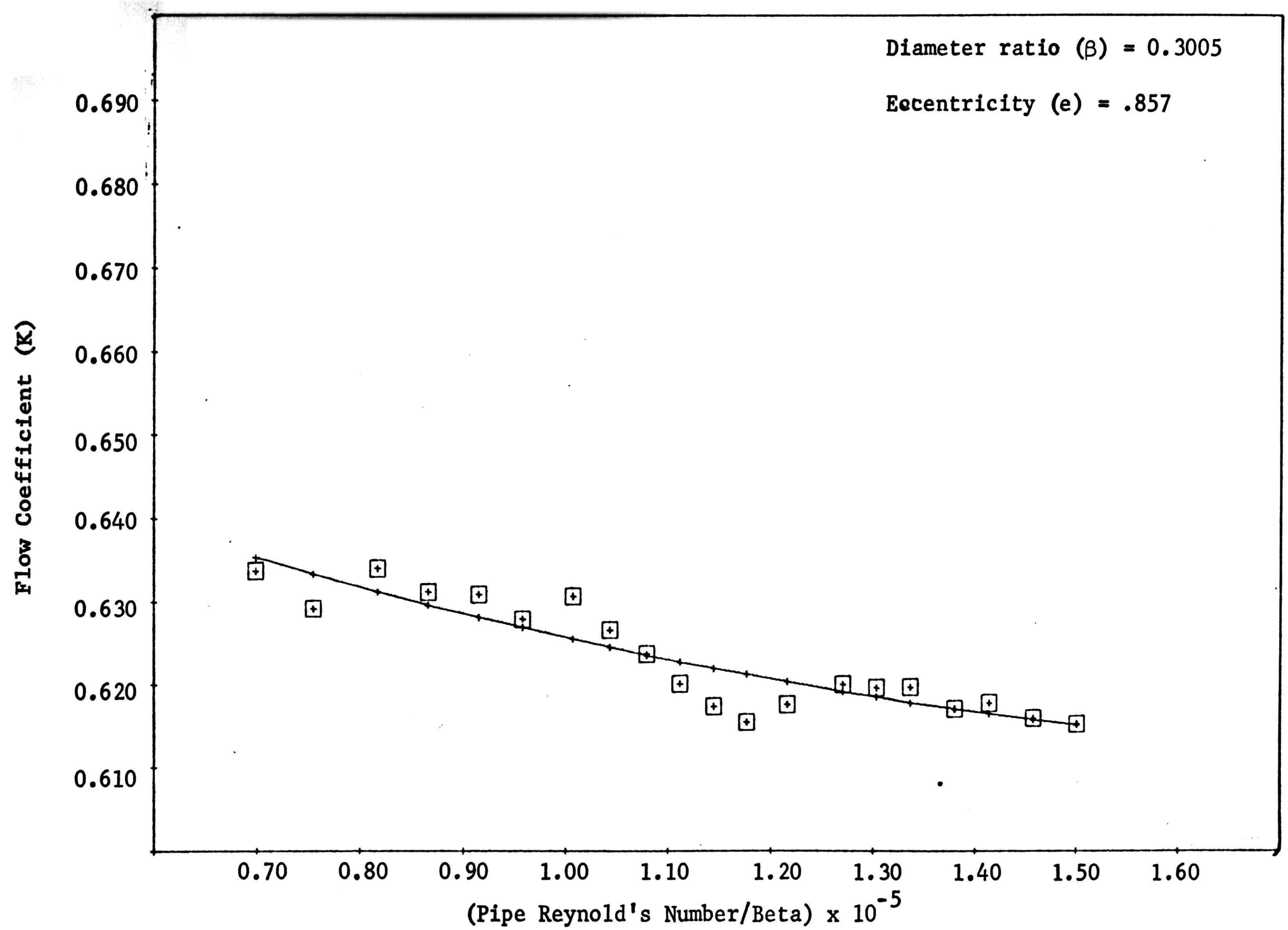

Figure 23. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

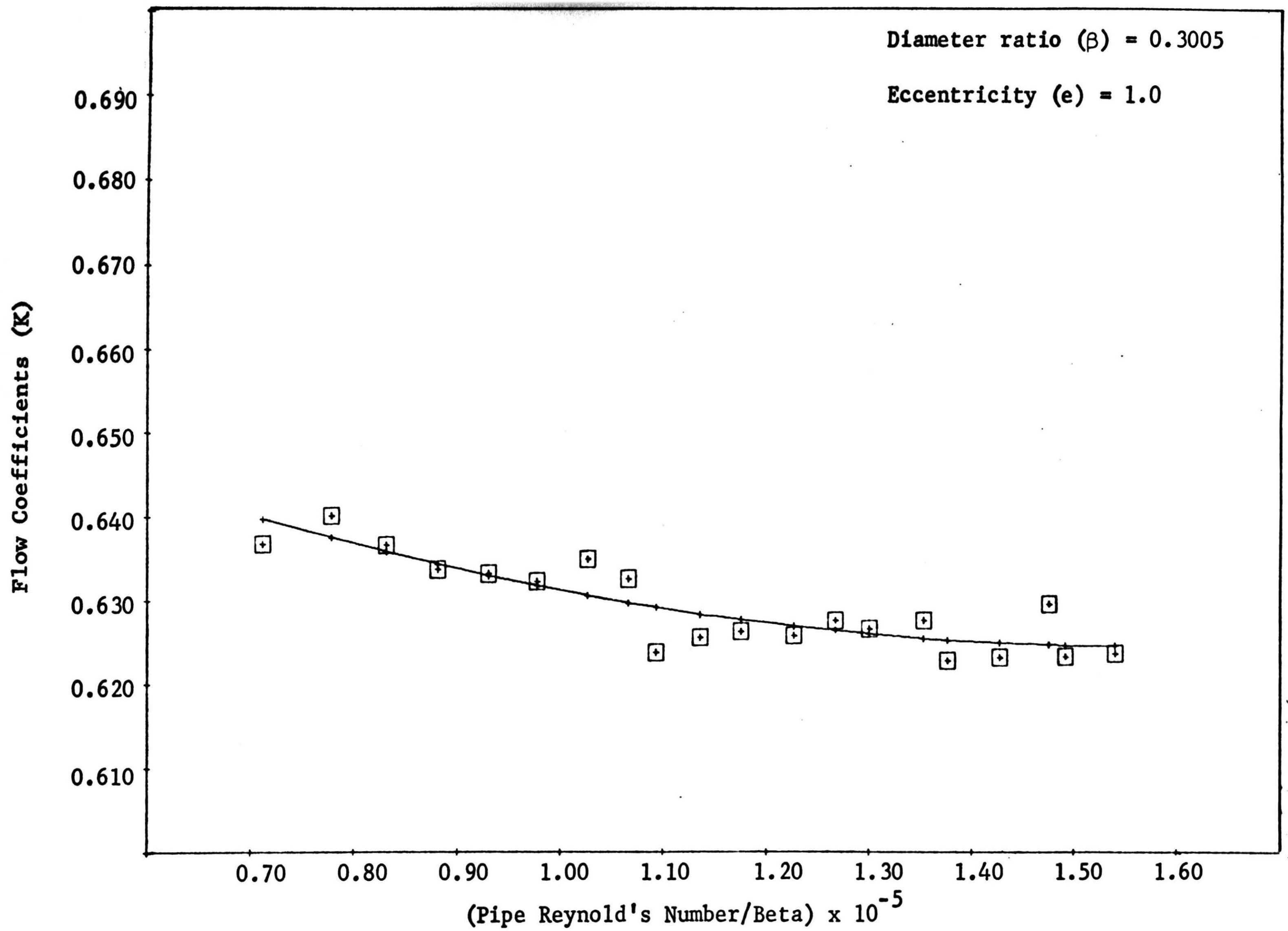

Figure 24. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

APPENDIX B

Curves of experimental data for a 0.5045" diameter orifice in a 1" diameter line.

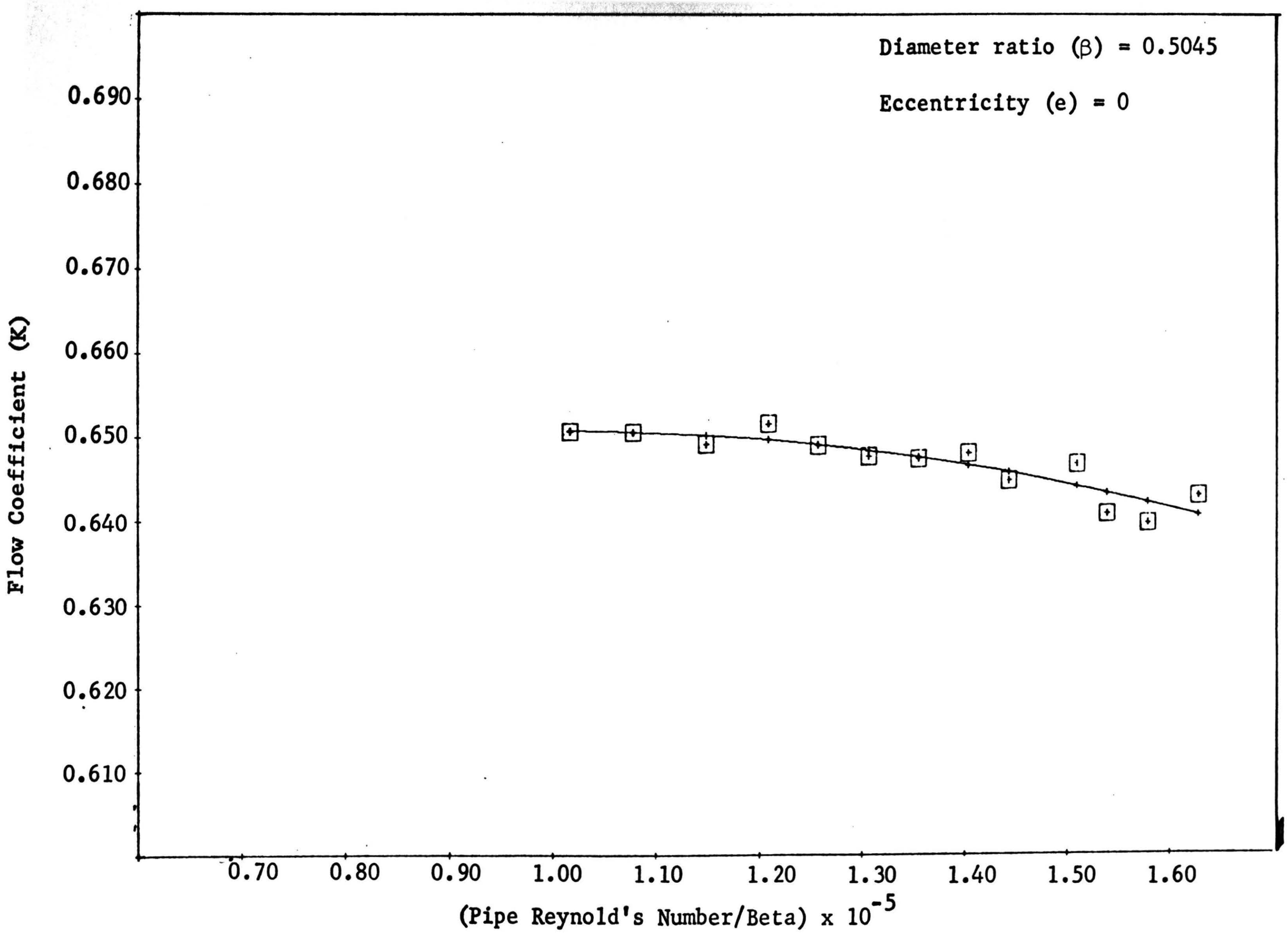

Figure 25. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

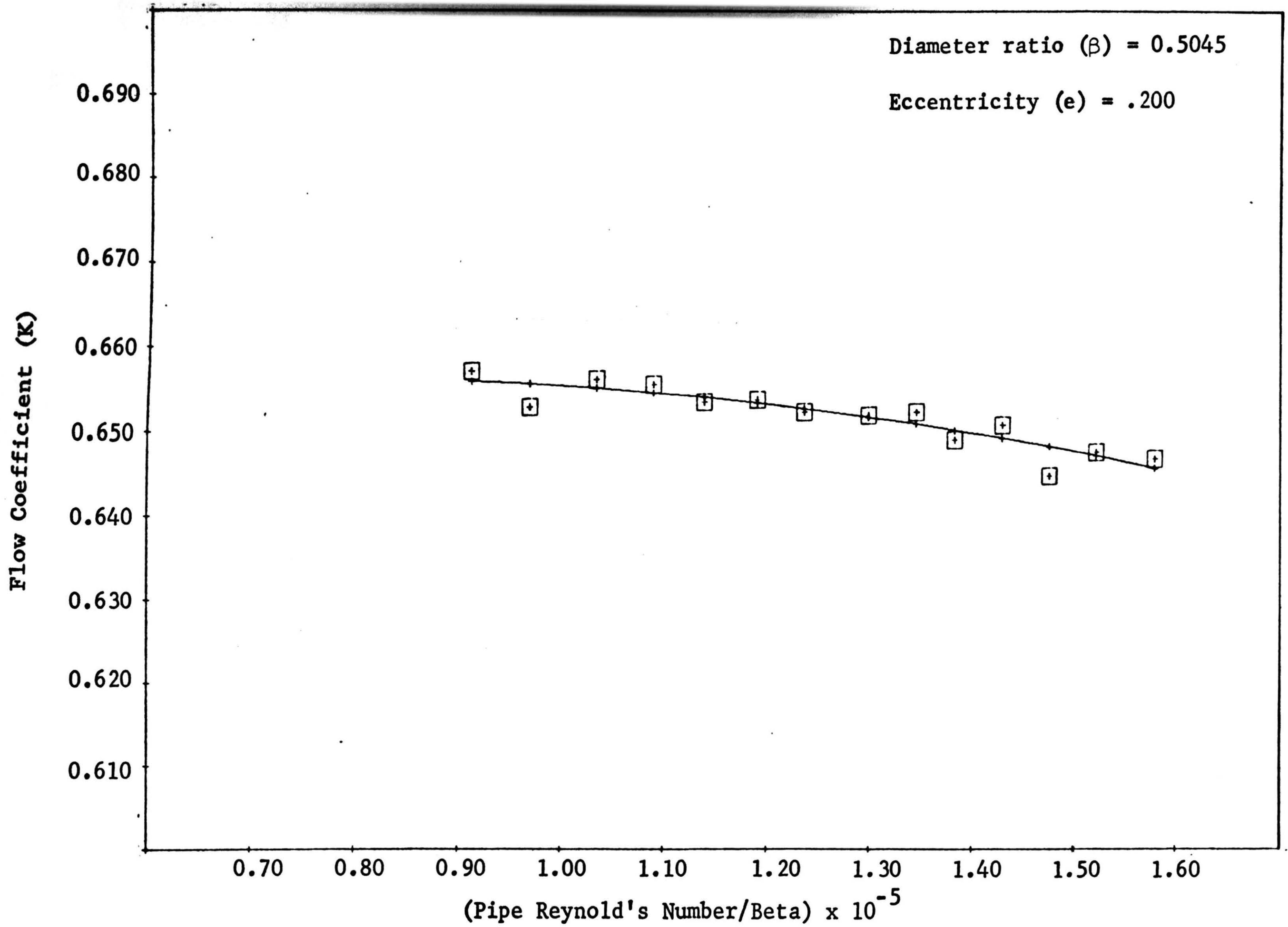

Figure 26. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

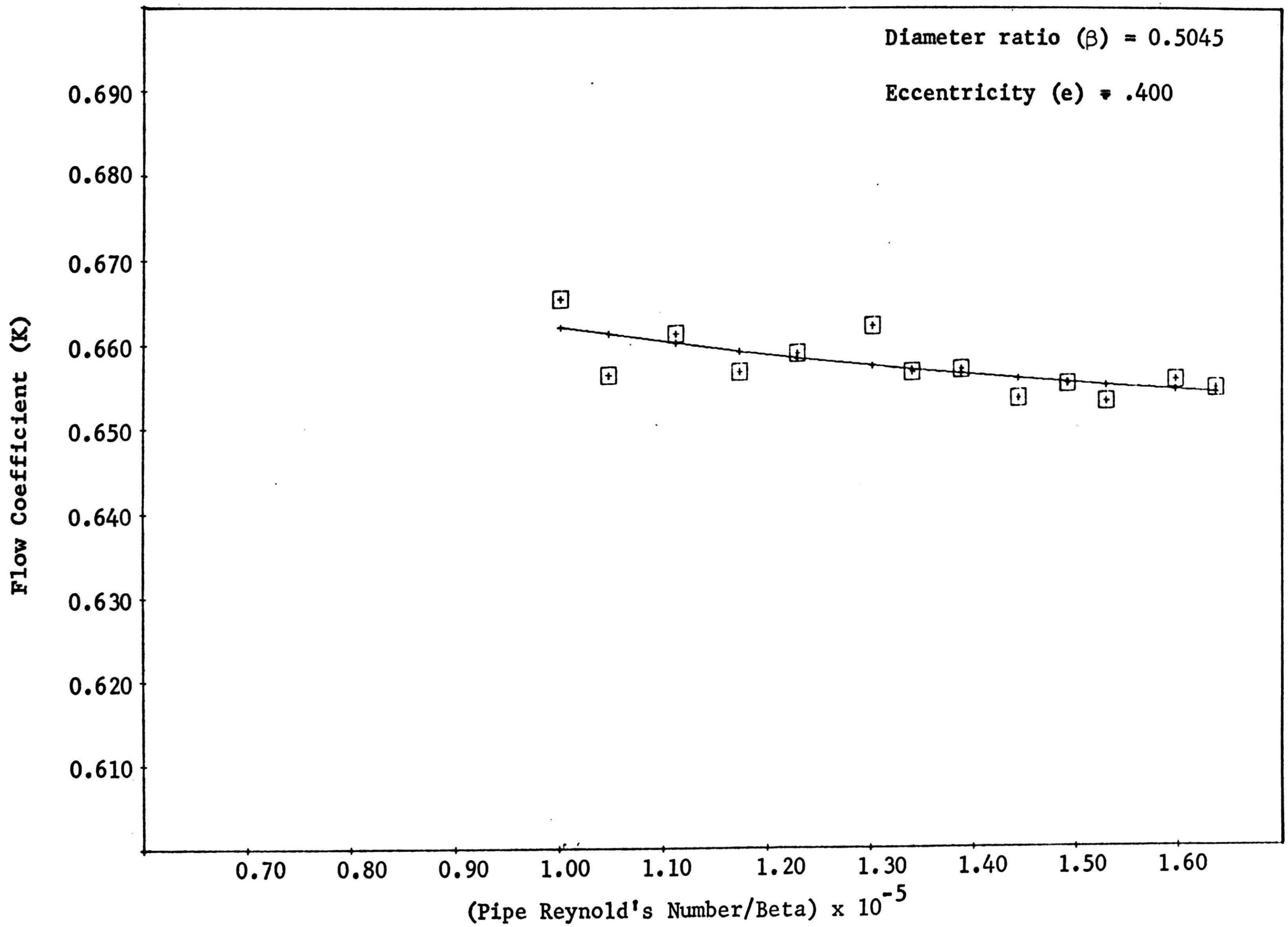

Figure 27. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

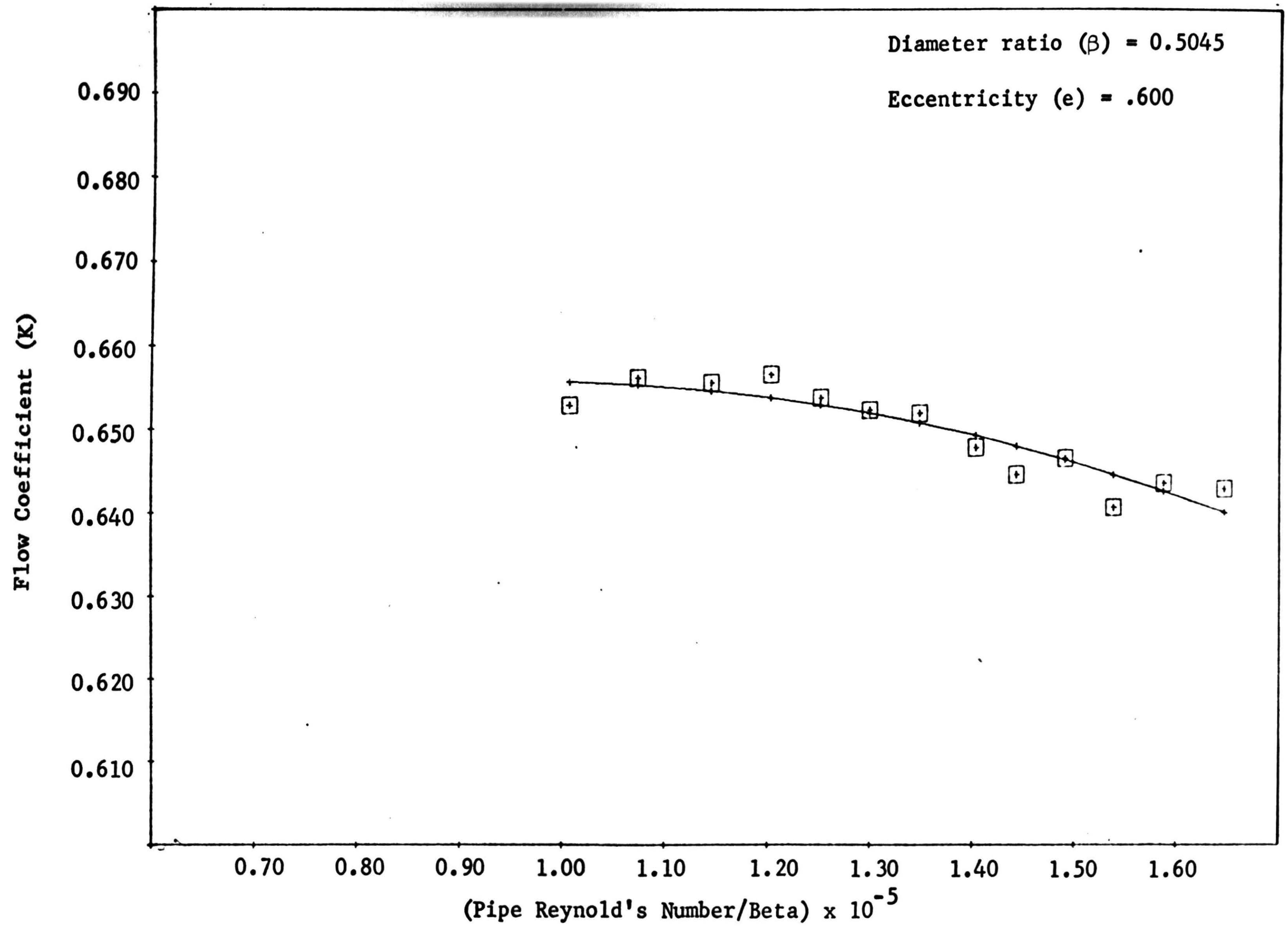

Figure 28. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

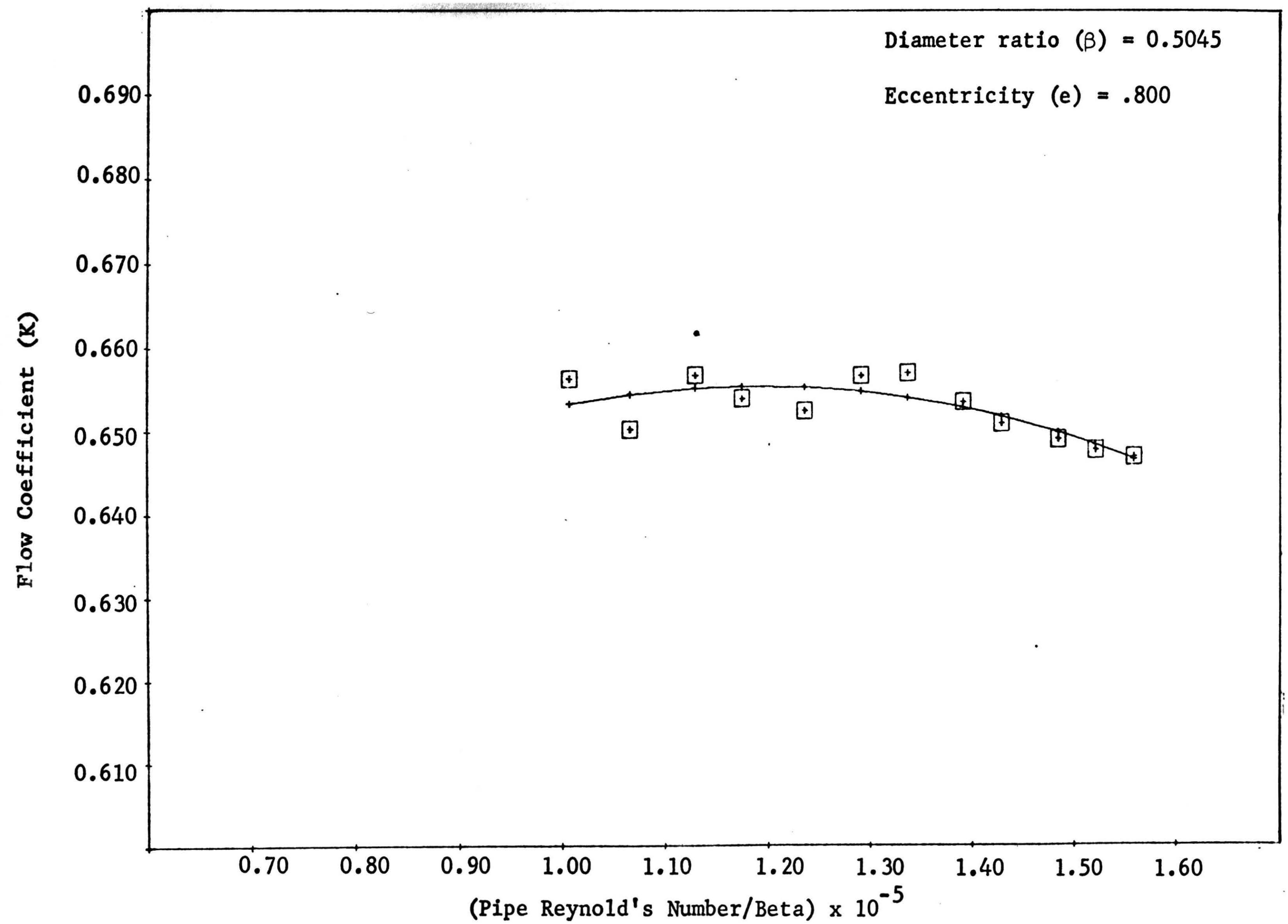

Figure 29. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

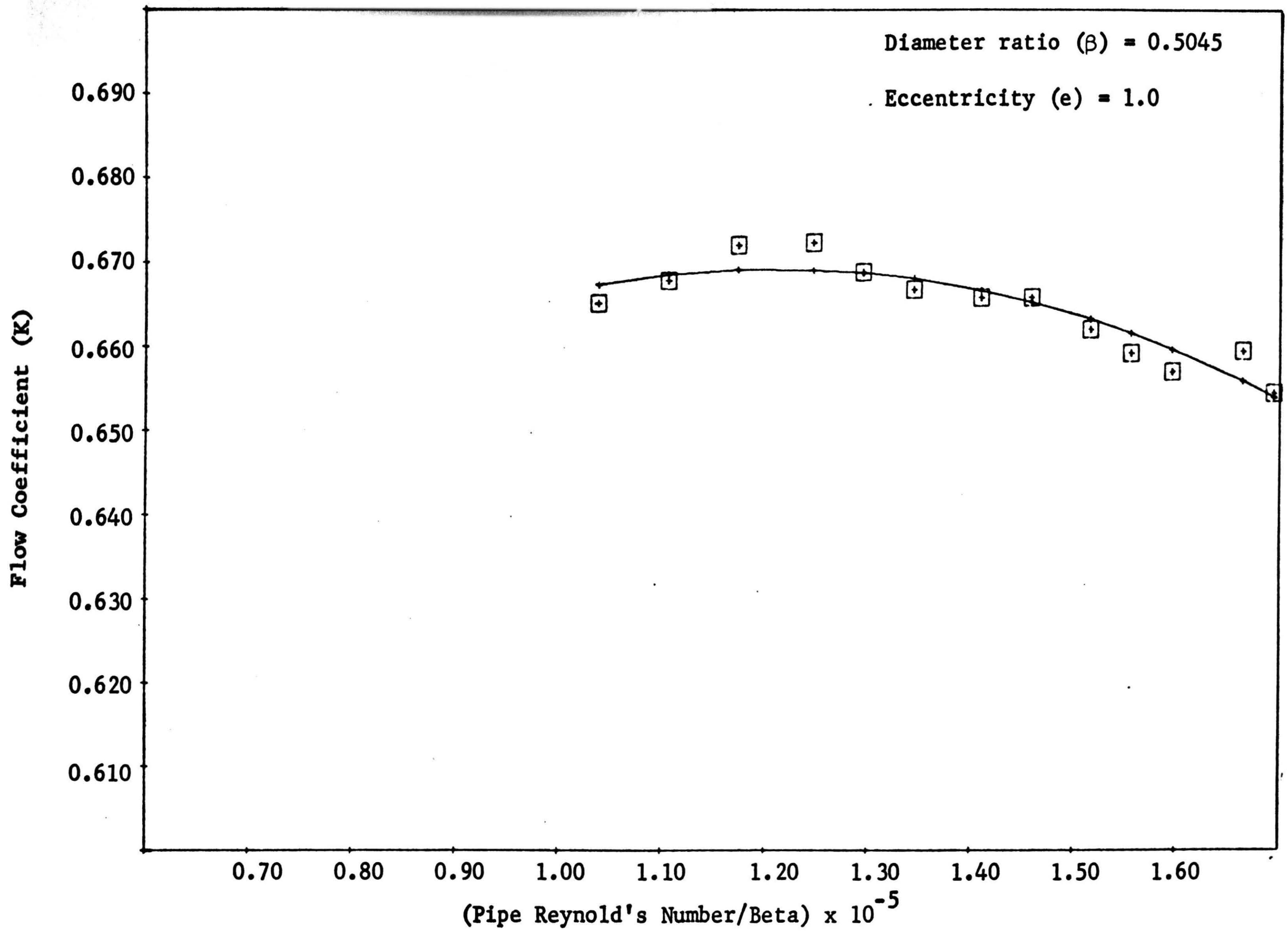

Figure 30. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

APPENDIX C

Curves of experimental data for a 0.6015" diameter orifice in a 1" diameter line.

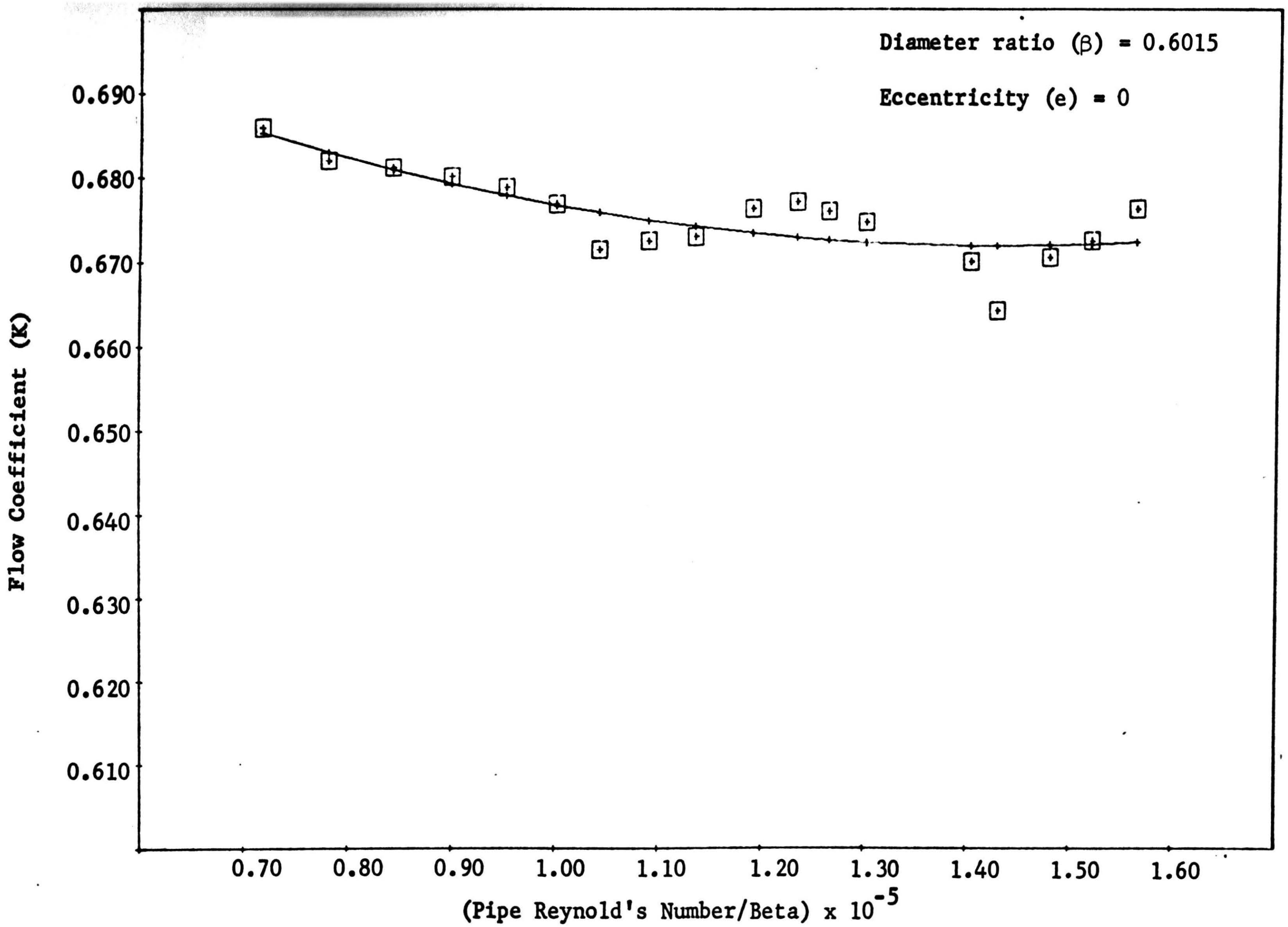

Figure 31. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

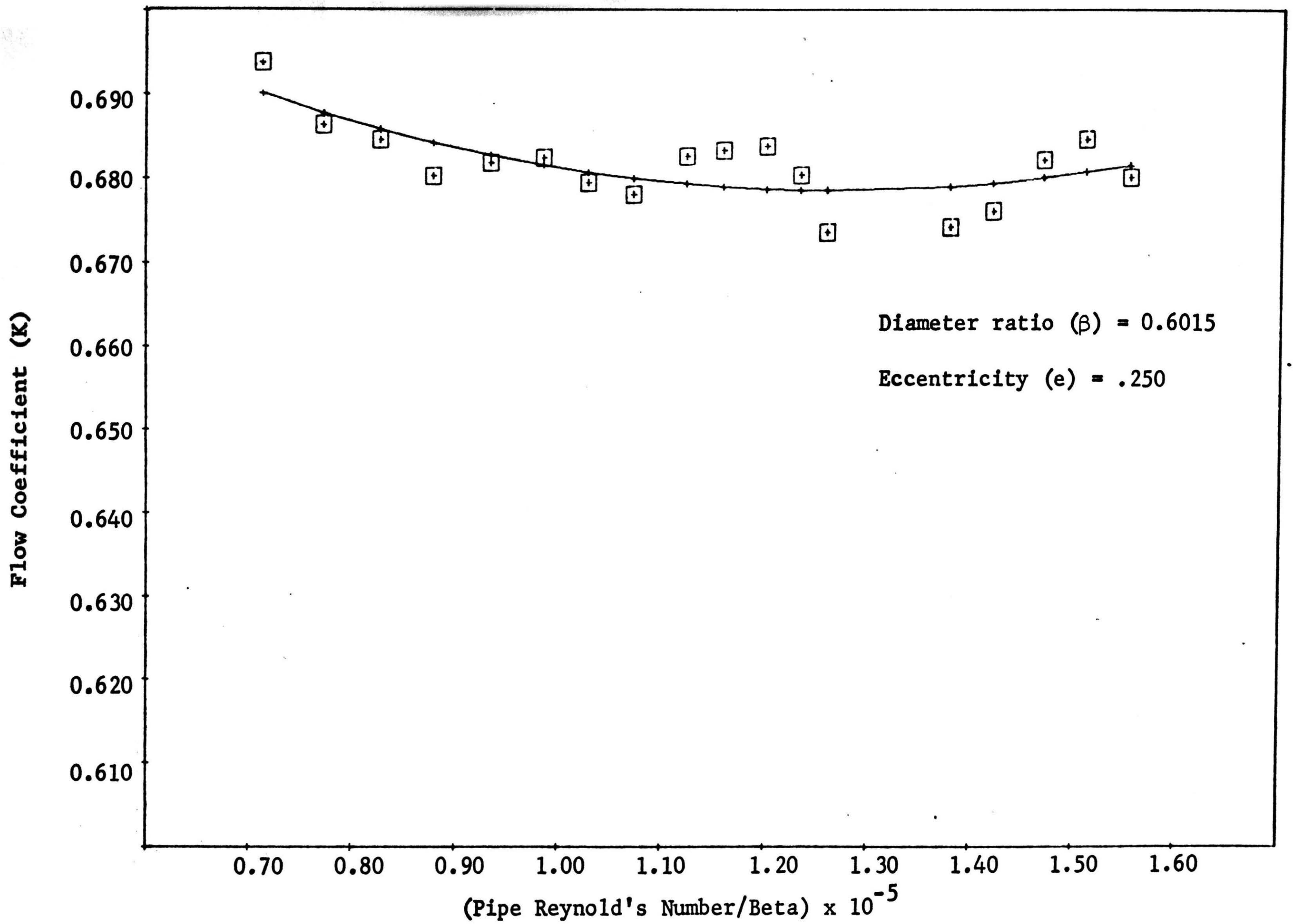

Figure 32. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

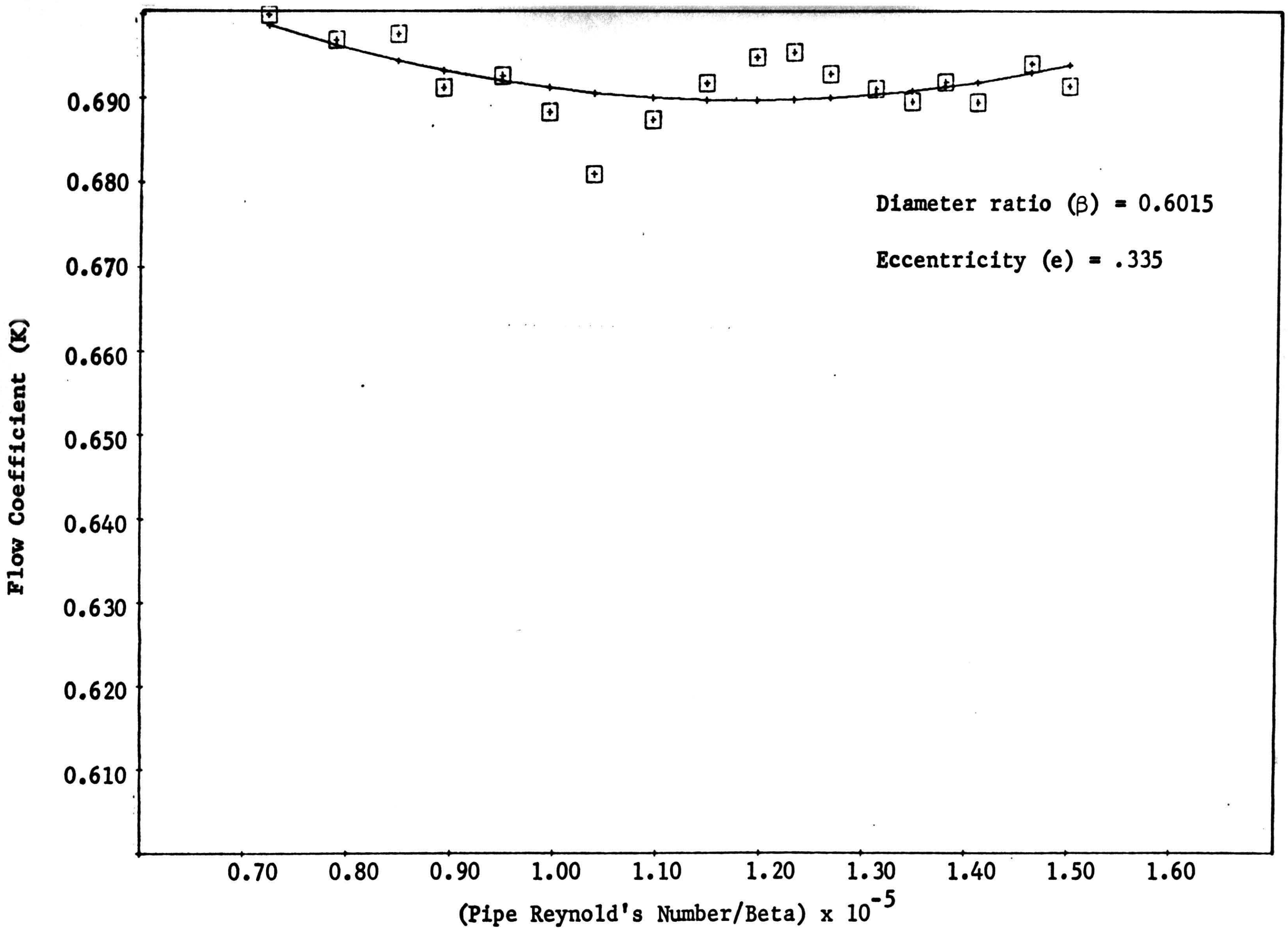

Figure 33. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

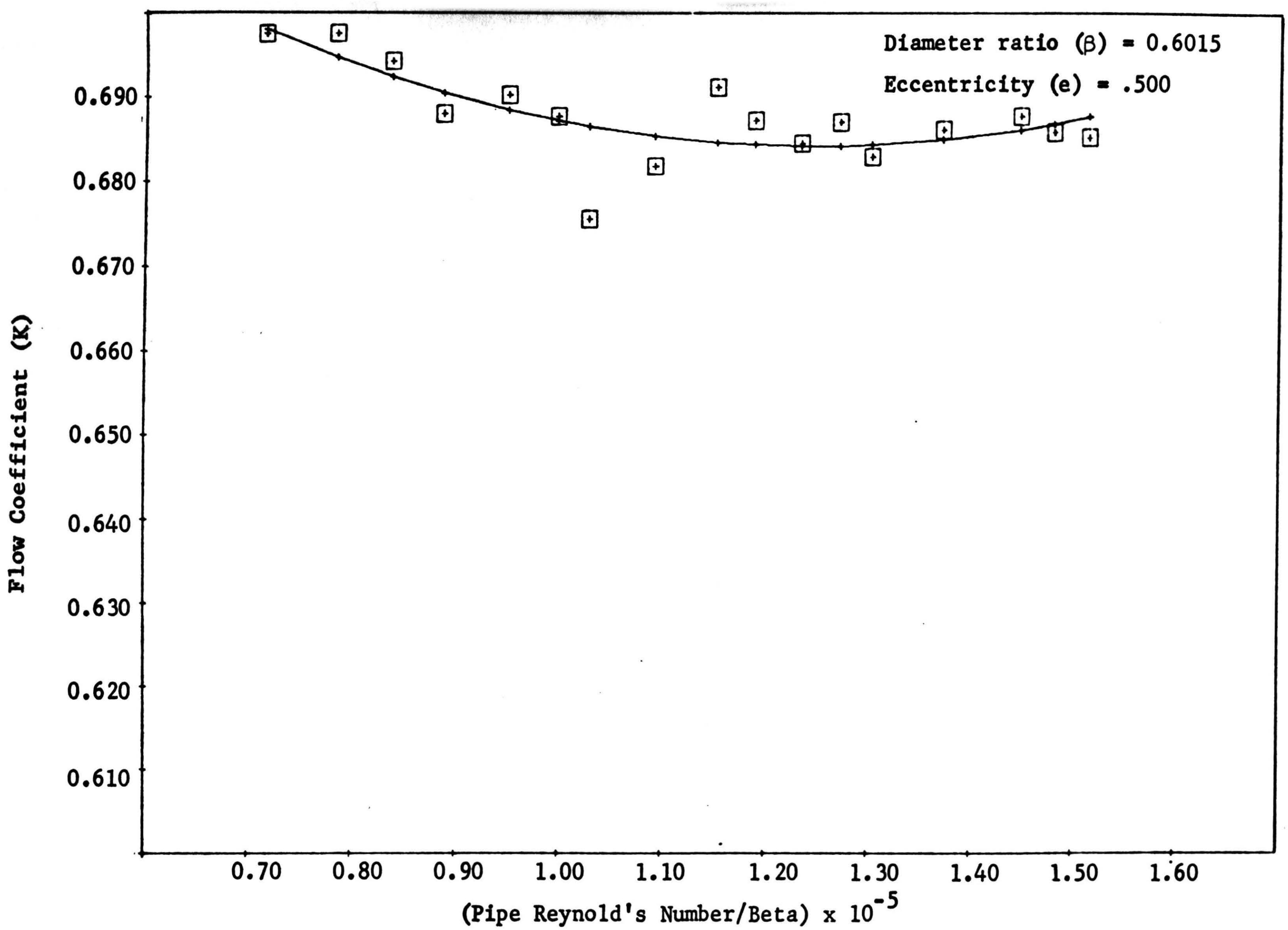

Figure 34. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

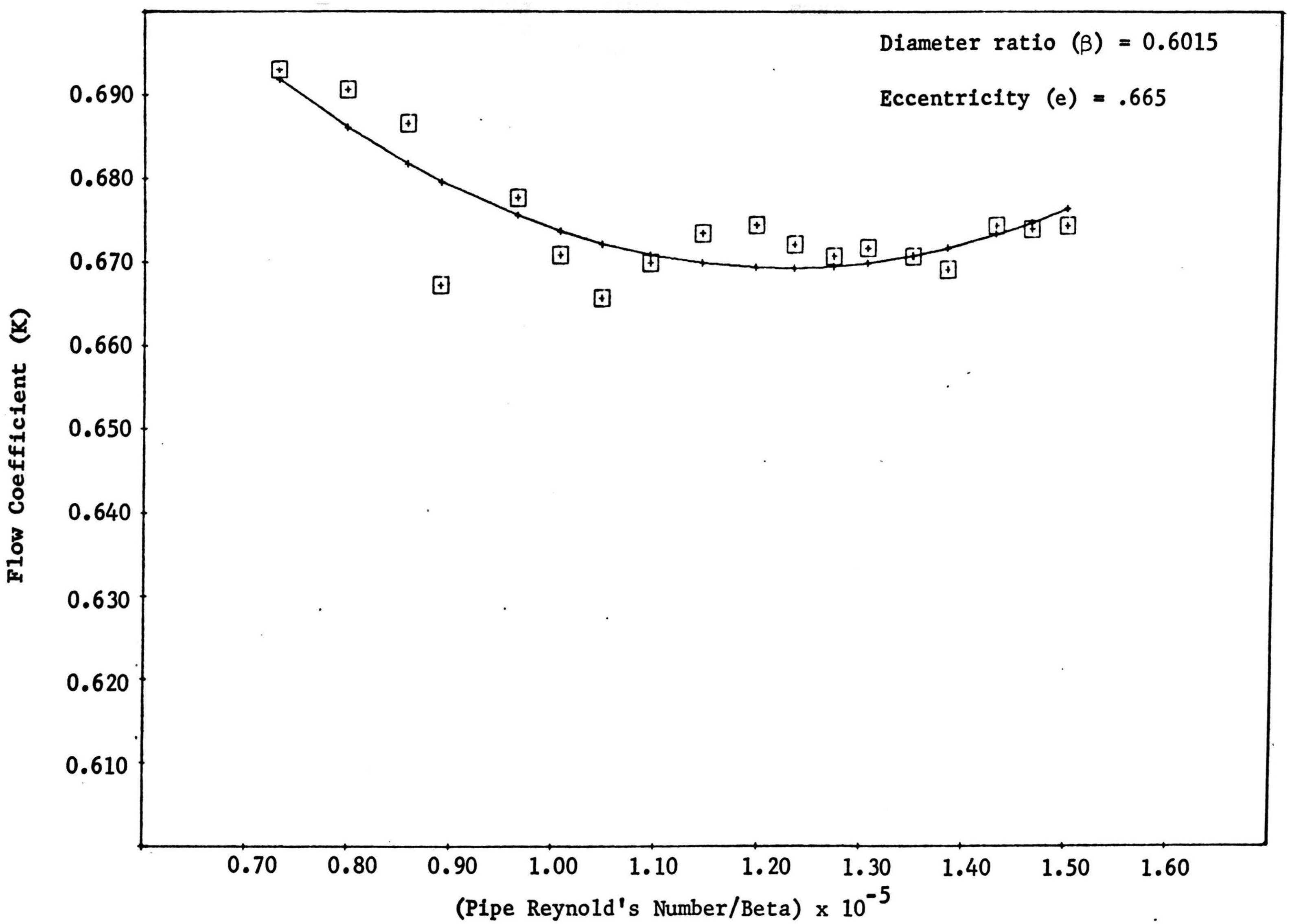

Figure 35. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

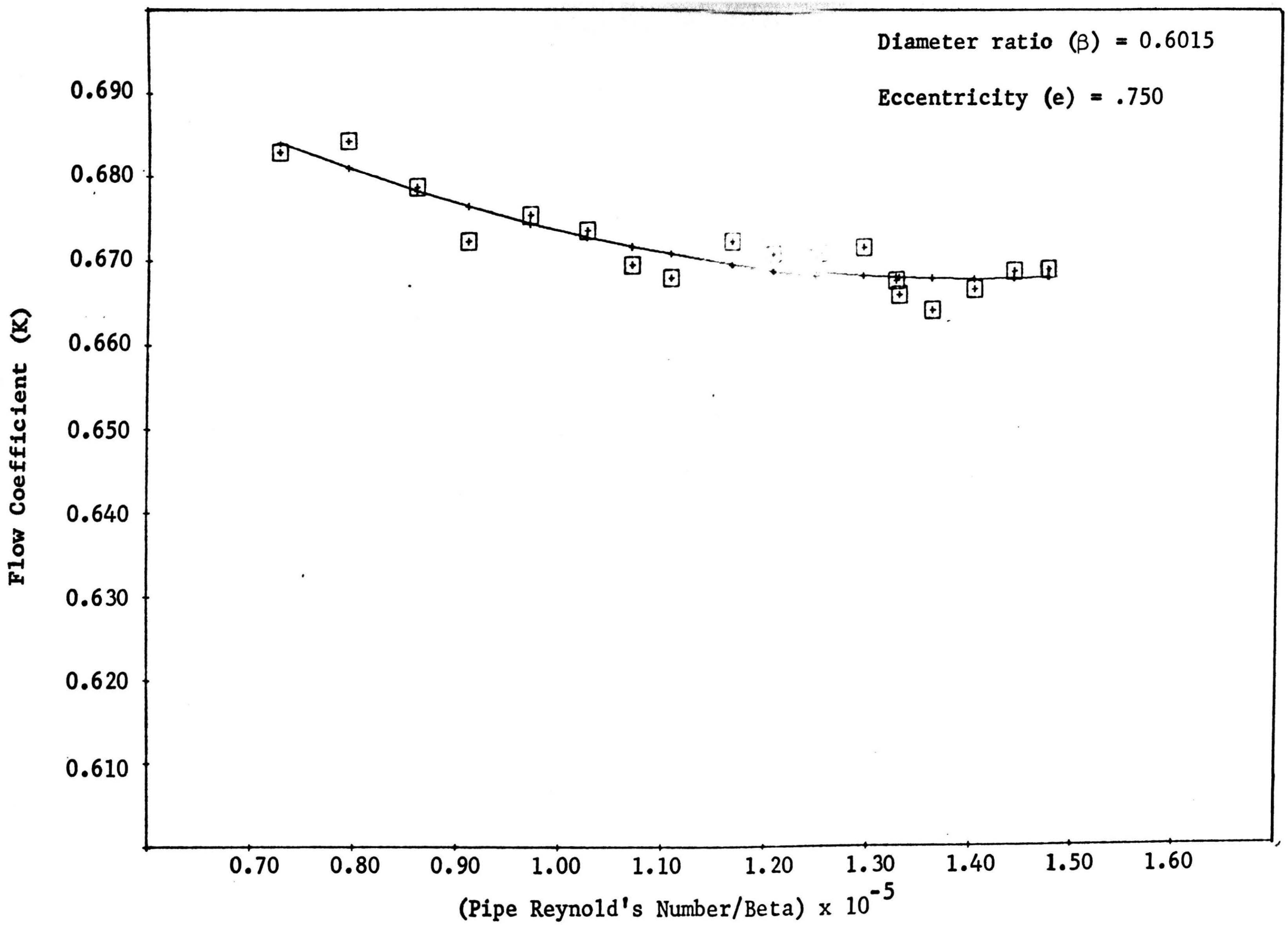

Figure 36. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

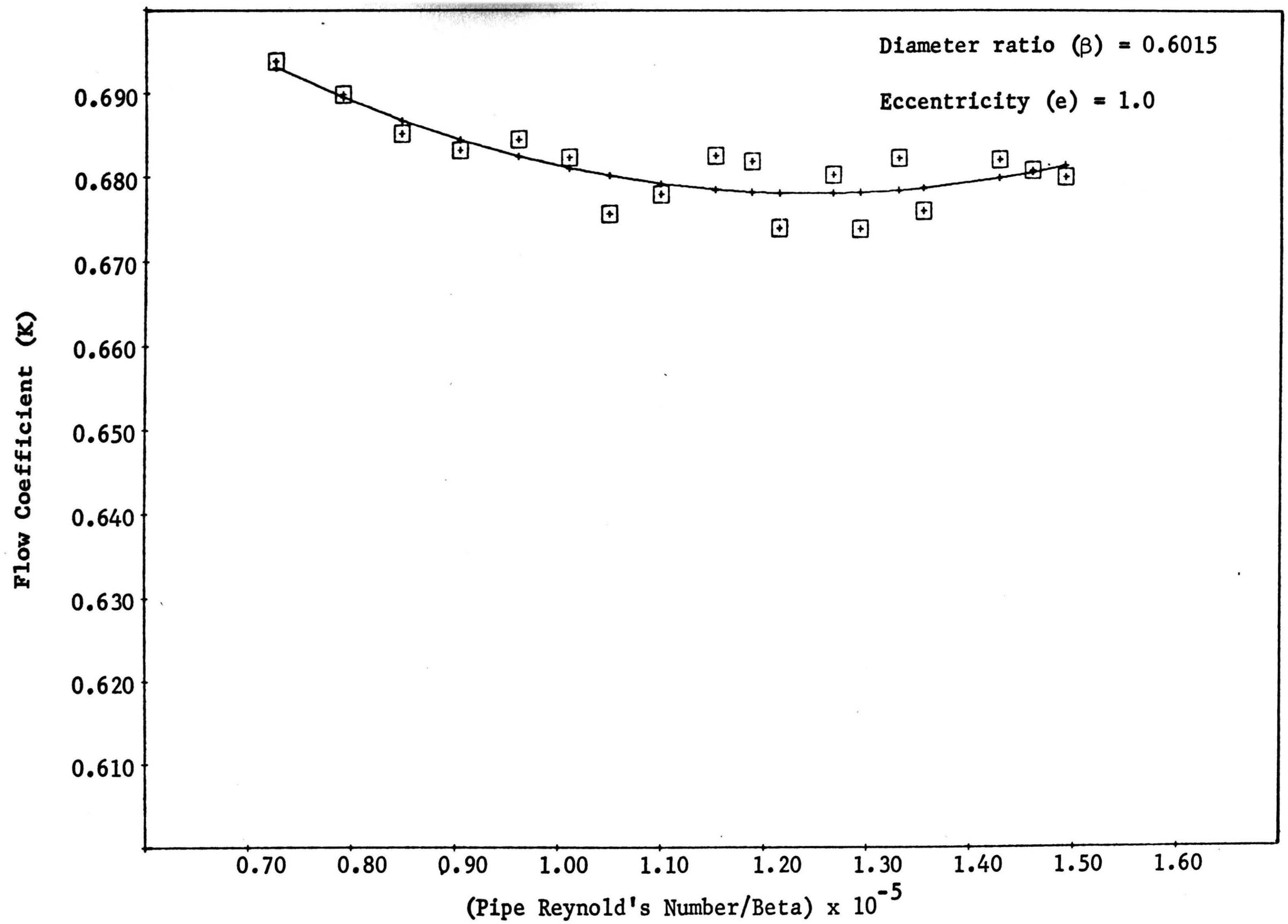

Figure 37. Flow Coefficients Versus Reynold's Number/Beta For a Square-Edged Orifice in a 1" Diameter Line

APPENDIX D

Experimental data which was read into the computer programs along with calculated values for Re/β, K and the K value on the least squares curve. KC will refer to the value of flow coefficient on the least squares curve.

β = 0.3005 e = 0

ΔP	$\dot{m}$	T	Re/β	K	KC
11.000	.774	80.000	.68990472E+05	.62486	.62716
13.000	.844	80.000	.75202885E+05	.62655	.62514
15.000	.906	80.000	.80761357E+05	.62639	.62344
17.000	.958	80.000	.85338925E+05	.62175	.62210
19.000	1.009	80.000	.89916492E+05	.61966	.62082
21.000	1.064	80.000	.94821028E+05	.62156	.61952
23.000	1.104	80.000	.98417687E+05	.61645	.61861
25.000	1.156	80.000	.10299525E+06	.61878	.61750
27.000	1.193	80.000	.10626494E+06	.61432	.61675
29.000	1.237	80.000	.11018857E+06	.61465	.61589
31.000	1.281	81.000	.11549798E+06	.61566	.61479
33.000	1.317	81.000	.11880738E+06	.61381	.61415
35.000	1.358	81.000	.12244772E+06	.61428	.61349
37.000	1.394	81.000	.12575712E+06	.61359	.61291
39.000	1.431	82.000	.13061515E+06	.61338	.61213
41.000	1.464	82.000	.13362935E+06	.61204	.61167
43.000	1.497	82.000	.13664355E+06	.61111	.61125
45.000	1.527	83.000	.14097471E+06	.60909	.61068
47.000	1.560	83.000	.14402464E+06	.60889	.61032
50.000	1.615	83.500	.14998147E+06	.61117	.60968

β = 0.3005 e = 0.143

ΔP	$\dot{m}$	T	Re/β	K	KC
11.000	.774	80.000	.68990472E+05	.62486	.62507
13.000	.844	80.000	.75202885E+05	.62655	.62411
15.000	.903	80.000	.80434389E+05	.62386	.62326
17.000	.954	80.000	.85011956E+05	.61936	.62248
19.000	1.009	80.000	.89916492E+05	.61966	.62161
21.000	1.064	80.000	.94821028E+05	.62156	.62069
23.000	1.108	80.000	.98744655E+05	.61850	.61994
25.000	1.156	80.000	.10299525E+06	.61878	.61909
27.000	1.204	80.000	.10724585E+06	.62000	.61821
29.000	1.248	80.000	.11116948E+06	.62012	.61738
31.000	1.284	80.000	.11443917E+06	.61742	.61666
33.000	1.321	80.000	.11770886E+06	.61552	.61593
35.000	1.358	80.000	.12097855E+06	.61428	.61518
37.000	1.394	80.000	.12424824E+06	.61359	.61442
39.000	1.431	81.000	.12906651E+06	.61338	.61326
41.000	1.468	81.000	.13237591E+06	.61357	.61244
43.000	1.505	81.000	.13568531E+06	.61411	.61160
45.000	1.523	81.000	.13734001E+06	.60763	.61118
47.000	1.560	81.000	.14064941E+06	.60889	.61032
50.000	1.611	82.000	.14702578E+06	.60978	.60861

$\beta = 0.3005$ $e = 0.286$

ΔP	$\dot{m}$	T	Re/β	K	KC
11.000	.789	79.000	.69444715E+05	.63671	.63642
13.000	.855	79.000	.75258692E+05	.63472	.63465
15.000	.917	79.000	.80749670E+05	.63400	.63319
17.000	.972	79.000	.85594648E+05	.63127	.63205
19.000	1.027	79.000	.90439630E+05	.63093	.63106
21.000	1.075	79.000	.94638612E+05	.62799	.63033
23.000	1.123	79.000	.98837594E+05	.62669	.62970
25.000	1.185	79.000	.10432857E+06	.63450	.62905
27.000	1.229	79.000	.10820455E+06	.63323	.62871
29.000	1.259	80.000	.11215038E+06	.62559	.62846
31.000	1.306	80.000	.11640098E+06	.62801	.62830
33.000	1.339	80.000	.11934370E+06	.62407	.62825
35.000	1.394	80.000	.12424824E+06	.63088	.62830
37.000	1.428	80.000	.12719096E+06	.62812	.62840
39.000	1.468	80.000	.13078762E+06	.62911	.62860
41.000	1.505	81.000	.13568531E+06	.62891	.62900
43.000	1.541	81.000	.13899471E+06	.62909	.62935

$\beta = 0.3005$ $e = 0.428$

ΔP	$\dot{m}$	T	Re/β	K	KC
11.000	.785	80.000	.69971377E+05	.63374	.63449
13.000	.848	80.000	.75529853E+05	.62927	.63269
15.000	.917	81.000	.82734948E+05	.63400	.63052
17.000	.969	81.000	.87368103E+05	.62889	.62923
19.000	1.027	81.000	.92663141E+05	.63093	.62784
21.000	1.075	81.000	.96965357E+05	.62799	.62680
23.000	1.119	82.000	.10214775E+06	.62464	.62562
25.000	1.174	82.000	.10717141E+06	.62860	.62458
27.000	1.211	82.000	.11052051E+06	.62378	.62394
29.000	1.248	82.000	.11386962E+06	.62012	.62334
31.000	1.292	82.000	.11788855E+06	.62095	.62267
33.000	1.332	82.000	.12157256E+06	.62065	.62211
35.000	1.365	82.000	.12458676E+06	.61760	.62169
37.000	1.409	82.000	.12860569E+06	.62005	.62118
39.000	1.461	83.000	.13487484E+06	.62596	.62050

β = 0.3005   e = 0.571

ΔP	ṁ	T	Re/β	K	KC
11.000	.781	79.000	.68798718E+05	.63078	.63206
13.000	.848	79.000	.74612695E+05	.62927	.63048
15.000	.917	79.000	.80749670E+05	.63400	.62876
17.000	.961	79.000	.84625653E+05	.62413	.62765
19.000	1.024	79.000	.90116632E+05	.62867	.62604
21.000	1.068	79.000	.93992615E+05	.62371	.62487
23.000	1.115	79.000	.98191597E+05	.62260	.62359
25.000	1.167	79.000	.10271358E+06	.62467	.62218
27.000	1.207	79.000	.10626656E+06	.62189	.62105
29.000	1.248	79.000	.10981955E+06	.62012	.61990
31.000	1.284	79.000	.11304953E+06	.61742	.61884
33.000	1.321	79.000	.11627952E+06	.61552	.61777
35.000	1.361	79.000	.11983250E+06	.61594	.61657
37.000	1.394	79.000	.12273949E+06	.61359	.61558
39.000	1.435	79.000	.12629248E+06	.61495	.61435
41.000	1.472	80.000	.13111459E+06	.61510	.61266

β = 3.005   e = 0.714

ΔP	ṁ	T	Re/β	K	KC
11.000	.778	80.000	.69317440E+05	.62782	.62990
13.000	.844	80.000	.75202885E+05	.62655	.62855
15.000	.914	80.000	.81415294E+05	.63147	.62713
17.000	.961	80.000	.85665893E+05	.62413	.62615
19.000	1.024	80.000	.91224369E+05	.62867	.62486
21.000	1.064	80.000	.94821028E+05	.62156	.62402
23.000	1.119	80.000	.99725564E+05	.62464	.62288
25.000	1.167	80.000	.10397616E+06	.62467	.62189
27.000	1.211	80.000	.10789979E+06	.62378	.62097
29.000	1.248	80.000	.11116948E+06	.62012	.62021
31.000	1.284	80.000	.11443917E+06	.61742	.61944
33.000	1.325	80.000	.11803583E+06	.61723	.61859
35.000	1.365	80.000	.12163249E+06	.61760	.61775
37.000	1.394	80.000	.12424824E+06	.61359	.61713
39.000	1.431	80.000	.12751793E+06	.61338	.61635
41.000	1.468	81.000	.13237591E+06	.61357	.61520
43.000	1.505	81.000	.13568531E+06	.61411	.61441
45.000	1.541	81.000	.13899471E+06	.61495	.61363
47.000	1.578	81.000	.14230410E+06	.61605	.61283
50.000	1.618	81.000	.14594444E+06	.61256	.61196

β = 0.3005 e = 0.857

ΔP	ṁ	T	Re/β	K	KC
11.000	.785	80.000	.69971377E+05	.63374	.63533
13.000	.848	80.000	.75529853E+05	.62927	.63336
15.000	.917	80.000	.81742266E+05	.63400	.63126
17.000	.972	80.000	.86646801E+05	.63127	.62968
19.000	1.027	80.000	.91551337E+05	.63093	.62816
21.000	1.075	80.000	.95801933E+05	.62799	.62690
23.000	1.130	80.000	.10070647E+06	.63079	.62551
25.000	1.171	80.000	.10430313E+06	.62664	.62453
27.000	1.211	80.000	.10789979E+06	.62378	.62359
29.000	1.248	80.000	.11116948E+06	.62012	.62277
31.000	1.284	80.000	.11443917E+06	.61742	.62197
33.000	1.321	80.000	.11770886E+06	.61552	.62120
35.000	1.365	80.000	.12163249E+06	.61760	.62032
37.000	1.409	81.000	.12708088E+06	.62005	.61917
39.000	1.446	81.000	.13039027E+06	.61967	.61851
41.000	1.483	81.000	.13369967E+06	.61971	.61788
43.000	1.512	82.000	.13798319E+06	.61711	.61711
45.000	1.549	82.000	.14133229E+06	.61788	.61654
47.000	1.578	83.000	.14571905E+06	.61605	.61585
50.000	1.626	83.000	.15012451E+06	.61534	.61520

β = 0.3005 e = 1.0

ΔP	ṁ	T	Re/β	K	KC
11.000	.789	81.000	.71152053E+05	.63671	.63977
13.000	.862	81.000	.77770851E+05	.64017	.63747
15.000	.921	81.000	.83065886E+05	.63654	.63577
17.000	.976	81.000	.88029983E+05	.63366	.63428
19.000	1.031	81.000	.92994079E+05	.63318	.63289
21.000	1.082	81.000	.97627237E+05	.63228	.63170
23.000	1.138	81.000	.10259133E+06	.63488	.63052
25.000	1.182	81.000	.10656261E+06	.63253	.62965
27.000	1.211	81.000	.10921012E+06	.62378	.62911
29.000	1.259	81.000	.11351234E+06	.62559	.62829
31.000	1.303	81.000	.11748362E+06	.62624	.62761
33.000	1.343	82.000	.12257730E+06	.62578	.62683
35.000	1.387	82.000	.12659622E+06	.62756	.62630
37.000	1.424	82.000	.12994533E+06	.62651	.62591
39.000	1.464	83.000	.13521372E+06	.62753	.62539
41.000	1.490	83.000	.13758589E+06	.62277	.62519
43.000	1.527	84.000	.14262660E+06	.62310	.62486
45.000	1.578	84.000	.14742654E+06	.62959	.62464
47.000	1.596	84.000	.14914080E+06	.62321	.62459
50.000	1.648	84.000	.15394073E+06	.62367	.62450

β = 0.4000 e = 0

ΔP	$\dot{m}$	T	Re/β	K	KC
7.000	1.104	77.000	.71243460E+05	.63064	.63163
9.000	1.248	77.000	.80474340E+05	.62824	.63009
11.000	1.387	77.000	.89468530E+05	.63177	.62859
13.000	1.501	77.000	.96805897E+05	.62881	.62737
15.000	1.611	77.000	.10390657E+06	.62833	.62619
17.000	1.699	78.000	.11096746E+06	.62248	.62502
19.000	1.795	78.000	.11719890E+06	.62187	.62399
21.000	1.890	78.000	.12343033E+06	.62296	.62296
23.000	1.982	79.000	.13103249E+06	.62416	.62170
25.000	2.055	79.000	.13588554E+06	.62085	.62090
27.000	2.129	79.000	.14073860E+06	.61874	.62010
29.000	2.202	80.000	.14738130E+06	.61761	.61900
31.000	2.276	80.000	.15229401E+06	.61727	.61820
33.000	2.349	80.000	.15720672E+06	.61757	.61739
35.000	2.422	80.000	.16211943E+06	.61841	.61658

β = 0.4000 e = 0.167

ΔP	$\dot{m}$	T	Re/β	K	KC
7.000	1.101	75.000	.69219422E+05	.62855	.63042
9.000	1.248	75.000	.78448677E+05	.62824	.62854
11.000	1.376	75.000	.86524277E+05	.62676	.62707
13.000	1.497	75.000	.94138415E+05	.62727	.62586
15.000	1.615	75.000	.10152182E+06	.62976	.62482
17.000	1.707	75.000	.10729010E+06	.62516	.62412
19.000	1.798	76.000	.11451758E+06	.62314	.62336
21.000	1.890	76.000	.12036031E+06	.62296	.62285
23.000	1.963	77.000	.12662874E+06	.61838	.62240
25.000	2.055	77.000	.13254597E+06	.62085	.62208
27.000	2.129	78.000	.13900892E+06	.61874	.62183
29.000	2.220	78.000	.14500068E+06	.62276	.62170
31.000	2.294	79.000	.15165797E+06	.62225	.62166
33.000	2.367	79.000	.15651103E+06	.62240	.62171
35.000	2.441	80.000	.16334761E+06	.62309	.62189

β = 0.4000 e = 0.333

ΔP	ṁ	T	Re/β	K	KC
7.000	1.130	78.000	.73818530E+05	.64531	.64183
9.000	1.266	78.000	.82686342E+05	.63748	.63984
11.000	1.398	78.000	.91314482E+05	.63679	.63821
13.000	1.516	78.000	.98983940E+05	.63496	.63702
15.000	1.633	79.000	.10798047E+06	.63691	.63592
17.000	1.725	79.000	.11404679E+06	.63189	.63537
19.000	1.835	79.000	.12132638E+06	.63586	.63491
21.000	1.945	79.000	.12860596E+06	.64111	.63466
23.000	2.019	80.000	.13509953E+06	.63572	.63463
25.000	2.092	80.000	.14001224E+06	.63193	.63471
27.000	2.184	80.000	.14615312E+06	.63475	.63496
29.000	2.276	80.000	.15229401E+06	.63820	.63536
31.000	2.331	80.000	.15597854E+06	.63221	.63567

β = 0.4000 e = 0.500

ΔP	ṁ	T	Re/β	K	KC
7.000	1.112	80.000	.74427560E+05	.63483	.63535
9.000	1.259	80.000	.84252980E+05	.63378	.63423
11.000	1.398	80.000	.93587127E+05	.63679	.63324
13.000	1.505	80.000	.10071055E+06	.63034	.63254
15.000	1.615	80.000	.10807962E+06	.62976	.63187
17.000	1.725	80.000	.11544869E+06	.63189	.63124
19.000	1.835	80.000	.12281775E+06	.63586	.63066
21.000	1.908	80.000	.12773046E+06	.62901	.63031
23.000	1.982	81.000	.13425400E+06	.62416	.62986
25.000	2.092	81.000	.14171255E+06	.63193	.62941
27.000	2.165	82.000	.14844496E+06	.62941	.62904

β = 0.4000 e = 0.667

ΔP	$\dot{m}$	T	Re/β	K	KC
7.000	1.104	80.000	.73936287E+05	.63064	.63192
9.000	1.251	80.000	.83761707E+05	.63008	.63131
11.000	1.387	81.000	.93977800E+05	.63177	.63054
13.000	1.505	81.000	.10193359E+06	.63034	.62985
15.000	1.615	81.000	.10939214E+06	.62976	.62912
17.000	1.725	81.000	.11685070E+06	.63189	.62831
19.000	1.817	82.000	.12454281E+06	.62950	.62740
21.000	1.908	82.000	.13083285E+06	.62901	.62660
23.000	1.982	82.000	.13586488E+06	.62416	.62592
25.000	2.055	83.000	.14256745E+06	.62085	.62496
27.000	2.129	83.000	.14765915E+06	.61874	.62419
29.000	2.202	83.000	.15275084E+06	.61761	.62338
31.000	2.312	83.000	.16038838E+06	.62723	.62211
33.000	2.386	83.000	.16548008E+06	.62722	.62122
35.000	2.422	84.000	.16999480E+06	.61841	.62040

β = 0.4000 e = 0.833

ΔP	$\dot{m}$	T	Re/β	K	KC
7.000	1.119	77.000	.72190217E+05	.63902	.63933
9.000	1.266	77.000	.81657787E+05	.63748	.63743
11.000	1.398	78.000	.91314482E+05	.63679	.63570
13.000	1.512	78.000	.98744270E+05	.63342	.63451
15.000	1.626	79.000	.10749517E+06	.63405	.63326
17.000	1.725	79.000	.11404679E+06	.63189	.63243
19.000	1.835	79.000	.12132638E+06	.63586	.63162
21.000	1.908	79.000	.12617943E+06	.62901	.63115
23.000	1.982	80.000	.13264317E+06	.62416	.63060
25.000	2.092	80.000	.14001224E+06	.63193	.63008
27.000	2.165	80.000	.14492495E+06	.62941	.62980
29.000	2.257	80.000	.15106583E+06	.63306	.62953
31.000	2.331	80.000	.15597854E+06	.63221	.62937
33.000	2.386	80.000	.15966308E+06	.62722	.62928
35.000	2.459	81.000	.16657441E+06	.62778	.62920

β = 0.4000 e = 1.0

ΔP	$\dot{m}$	T	Re/β	K	KC
7.000	1.138	79.000	.75222355E+05	.64950	.64928
9.000	1.284	79.000	.84928465E+05	.64671	.64777
11.000	1.420	78.000	.92752505E+05	.64682	.64658
13.000	1.541	78.000	.10066163E+06	.64572	.64539
15.000	1.651	78.000	.10785175E+06	.64407	.64434
17.000	1.762	78.000	.11504186E+06	.64533	.64330
19.000	1.853	78.000	.12103363E+06	.64221	.64245
21.000	1.945	78.000	.12702539E+06	.64111	.64161
23.000	2.037	78.000	.13301716E+06	.64150	.64079
25.000	2.110	79.000	.13952533E+06	.63748	.63991
27.000	2.202	79.000	.14559165E+06	.64008	.63910
29.000	2.276	79.000	.15044471E+06	.63820	.63847
31.000	2.349	80.000	.15720672E+06	.63718	.63760
33.000	2.422	80.000	.16211943E+06	.63687	.63697
35.000	2.496	80.000	.16703214E+06	.63715	.63636

β = 0.5045 e = 0

ΔP	$\dot{m}$	T	Re/β	K	KC
8.000	1.938	79.000	.10158228E+06	.65051	.65060
9.000	2.055	79.000	.10773878E+06	.65047	.65047
10.000	2.162	80.000	.11471105E+06	.64905	.65008
11.000	2.276	80.000	.12074847E+06	.65142	.64953
12.000	2.367	80.000	.12561736E+06	.64883	.64896
13.000	2.459	80.000	.13048625E+06	.64754	.64825
14.000	2.551	80.000	.13535514E+06	.64727	.64743
15.000	2.643	80.000	.14022403E+06	.64781	.64648
16.000	2.716	80.000	.14411914E+06	.64467	.64563
17.000	2.808	81.000	.15079735E+06	.64655	.64399
18.000	2.863	81.000	.15375417E+06	.64065	.64319
19.000	2.936	81.000	.15769658E+06	.63955	.64205
20.000	3.028	81.000	.16262460E+06	.64284	.64051

$\beta = 0.5045$ $e = 0.200$

ΔP	ṁ	T	Re/β	K	KC
7.000	1.831	75.000	.91286400E+05	.65723	.65607
8.000	1.945	75.000	.96957500E+05	.65297	.65573
9.000	2.074	75.000	.10336035E+06	.65628	.65521
10.000	2.184	75.000	.10884851E+06	.65566	.65467
11.000	2.283	75.000	.11378785E+06	.65352	.65410
12.000	2.386	75.000	.11891014E+06	.65386	.65342
13.000	2.477	75.000	.12348360E+06	.65237	.65275
14.000	2.569	76.000	.12970984E+06	.65192	.65174
15.000	2.661	76.000	.13434234E+06	.65231	.65090
16.000	2.734	76.000	.13804833E+06	.64902	.65019
17.000	2.826	76.000	.14268083E+06	.65077	.64923
18.000	2.881	77.000	.14731500E+06	.64476	.64821
19.000	2.973	77.000	.15200656E+06	.64755	.64710
20.000	3.046	78.000	.15772175E+06	.64674	.64566

$\beta = 0.5045$ $e = 0.400$

ΔP	ṁ	T	Re/β	K	KC
8.000	1.982	76.000	.10006188E+06	.66529	.66192
9.000	2.074	76.000	.10469437E+06	.65628	.66111
10.000	2.202	76.000	.11117986E+06	.66117	.66004
11.000	2.294	77.000	.11728901E+06	.65667	.65909
12.000	2.404	77.000	.12291888E+06	.65889	.65828
13.000	2.514	78.000	.13016795E+06	.66204	.65732
14.000	2.588	78.000	.13396847E+06	.65658	.65685
15.000	2.679	78.000	.13871913E+06	.65681	.65630
16.000	2.753	79.000	.14429301E+06	.65338	.65571
17.000	2.845	79.000	.14910278E+06	.65500	.65524
18.000	2.918	79.000	.15295060E+06	.65297	.65489
19.000	3.010	80.000	.15969959E+06	.65554	.65434
20.000	3.083	80.000	.16359470E+06	.65453	.65406

β = 0.5045 e = 0.600

ΔP	$\dot{m}$	T	Re/β	K	KC
8.000	1.945	78.000	.10071389E+06	.65297	.65575
9.000	2.074	78.000	.10736480E+06	.65628	.65539
10.000	2.184	79.000	.11447246E+06	.65566	.65467
11.000	2.294	79.000	.12024418E+06	.65667	.65383
12.000	2.386	79.000	.12505394E+06	.65386	.65296
13.000	2.477	79.000	.12986371E+06	.65237	.65194
14.000	2.569	79.000	.13467348E+06	.65192	.65076
15.000	2.643	80.000	.14022403E+06	.64781	.64920
16.000	2.716	80.000	.14411914E+06	.64467	.64799
17.000	2.808	80.000	.14898803E+06	.64655	.64632
18.000	2.863	81.000	.15375417E+06	.64065	.64454
19.000	2.955	81.000	.15868218E+06	.64355	.64253
20.000	3.028	82.000	.16457589E+06	.64284	.63992

β = 0.5045 e = 0.800

ΔP	$\dot{m}$	T	Re/β	K	KC
9.000	2.074	73.000	.10069607E+06	.65628	.65321
10.000	2.165	74.000	.10654197E+06	.65015	.65434
11.000	2.294	74.000	.11286225E+06	.65667	.65507
12.000	2.386	74.000	.11737675E+06	.65386	.65527
13.000	2.477	75.000	.12348360E+06	.65237	.65513
14.000	2.588	75.000	.12897176E+06	.65658	.65460
15.000	2.679	75.000	.13354523E+06	.65681	.65386
16.000	2.753	76.000	.13897483E+06	.65338	.65264
17.000	2.826	76.000	.14268083E+06	.65077	.65159
18.000	2.900	77.000	.14825331E+06	.64886	.64968
19.000	2.973	77.000	.15200656E+06	.64755	.64816
20.000	3.046	77.000	.15575981E+06	.64674	.64647

β = 0.5045 e = 1.0

ΔP	ṁ	T	Re/β	K	KC
8.000	1.982	79.000	.10389097E+06	.66529	.66747
9.000	2.110	79.000	.11062464E+06	.66790	.66863
10.000	2.239	79.000	.11735832E+06	.67219	.66921
11.000	2.349	80.000	.12464358E+06	.67243	.66919
12.000	2.441	80.000	.12951247E+06	.66895	.66880
13.000	2.532	80.000	.13438136E+06	.66687	.66810
14.000	2.624	81.000	.14094132E+06	.66589	.66669
15.000	2.716	81.000	.14586933E+06	.66581	.66526
16.000	2.789	82.000	.15160931E+06	.66209	.66321
17.000	2.863	82.000	.15559903E+06	.65922	.66154
18.000	2.936	82.000	.15958874E+06	.65708	.65967
19.000	3.028	83.000	.16652718E+06	.65954	.65592
20.000	3.083	83.000	.16955495E+06	.65453	.65409

β = 0.6015 e = 0

ΔP	ṁ	T	Re/β	K	KC
2.500	1.624	79.500	.71842902E+05	.68605	.68546
3.000	1.769	79.500	.78255998E+05	.68218	.68312
3.500	1.908	79.500	.84425557E+05	.68137	.68108
4.000	2.037	79.500	.90108048E+05	.68026	.67939
4.500	2.156	79.500	.95384645E+05	.67892	.67796
5.000	2.266	79.500	.10025534E+06	.67697	.67679
5.500	2.358	79.500	.10431427E+06	.67159	.67590
6.000	2.466	79.500	.10910379E+06	.67252	.67497
6.500	2.569	79.500	.11364979E+06	.67306	.67421
7.000	2.679	80.000	.11924450E+06	.67638	.67342
7.500	2.777	80.000	.12357324E+06	.67716	.67292
8.000	2.863	79.500	.12663833E+06	.67603	.67263
8.500	2.945	79.500	.13029136E+06	.67476	.67235
9.000	3.010	84.000	.14045264E+06	.67005	.67196
9.500	3.065	84.000	.14302190E+06	.66411	.67194
10.000	3.175	84.000	.14816041E+06	.67055	.67203
10.500	3.263	84.000	.15227121E+06	.67255	.67219
11.000	3.358	84.000	.15672459E+06	.67630	.67248

β = 0.6015 e = 0.250

ΔP	ṁ	T	Re/β	K	KC
2.500	1.642	78.000	.71323408E+05	.69381	.69010
3.000	1.780	78.000	.77300229E+05	.68643	.68775
3.500	1.918	77.500	.82759062E+05	.68465	.68584
4.000	2.037	77.500	.87906754E+05	.68026	.68424
4.500	2.165	77.500	.93450423E+05	.68181	.68274
5.000	2.285	77.500	.98598116E+05	.68245	.68154
5.500	2.386	77.500	.10295385E+06	.67943	.68069
6.000	2.487	77.500	.10730959E+06	.67803	.67998
6.500	2.606	77.500	.11245729E+06	.68268	.67932
7.000	2.707	77.000	.11608200E+06	.68333	.67897
7.500	2.804	77.000	.12025308E+06	.68388	.67869
8.000	2.881	77.000	.12355847E+06	.68036	.67856
8.500	2.940	77.000	.12607685E+06	.67350	.67852
9.000	3.028	82.000	.13803581E+06	.67414	.67896
9.500	3.120	82.000	.14221871E+06	.67604	.67937
10.000	3.230	82.000	.14723819E+06	.68218	.68002
10.500	3.322	82.000	.15142110E+06	.68465	.68072
11.000	3.377	83.000	.15575592E+06	.68000	.68157

β = 0.6015 e = 0.335

ΔP	ṁ	T	Re/β	K	KC
2.500	1.657	78.500	.72408621E+05	.70001	.69870
3.000	1.807	78.500	.78983935E+05	.69704	.69633
3.500	1.954	78.000	.84870871E+05	.69775	.69452
4.000	2.070	77.500	.89332269E+05	.69130	.69335
4.500	2.200	77.500	.94955128E+05	.69278	.69211
5.000	2.305	77.500	.99469261E+05	.68848	.69130
5.500	2.391	78.000	.10383731E+06	.68100	.69069
6.000	2.521	78.000	.10949537E+06	.68754	.69014
6.500	2.641	78.000	.11467528E+06	.69181	.68987
7.000	2.753	78.000	.11953643E+06	.69491	.68982
7.500	2.852	77.500	.12306945E+06	.69551	.68991
8.000	2.934	77.500	.12663323E+06	.69293	.69011
8.500	3.017	78.000	.13101193E+06	.69116	.69050
9.000	3.098	78.000	.13451833E+06	.68966	.69093
9.500	3.193	77.500	.13779977E+06	.69195	.69143
10.000	3.265	77.500	.14088838E+06	.68954	.69198
10.500	3.368	78.000	.14623290E+06	.69411	.69313
11.000	3.434	78.500	.15002937E+06	.69145	.69409

β = 0.6015 e = 0.500

ΔP	ṁ	T	Re/β	K	KC
2.500	1.651	78.000	.71721862E+05	.69768	.69811
3.000	1.809	78.000	.78575285E+05	.69775	.69481
3.500	1.945	77.500	.83946990E+05	.69447	.69254
4.000	2.061	77.500	.88936292E+05	.68823	.69068
4.500	2.193	78.000	.95230694E+05	.69047	.68869
5.000	2.303	78.000	.10001215E+06	.68793	.68742
5.500	2.373	78.000	.10304040E+06	.67577	.68674
6.000	2.501	78.500	.10929451E+06	.68203	.68561
6.500	2.639	78.500	.11530852E+06	.69133	.68488
7.000	2.723	78.500	.11899711E+06	.68749	.68461
7.500	2.808	79.000	.12344429E+06	.68477	.68446
8.000	2.911	78.500	.12717615E+06	.68729	.68448
8.500	2.982	78.500	.13030344E+06	.68317	.68460
9.000	3.083	80.000	.13721285E+06	.68639	.68520
9.500	3.175	82.000	.14472845E+06	.68797	.68638
10.000	3.248	82.000	.14807477E+06	.68605	.68708
10.500	3.325	82.000	.15158841E+06	.68541	.68794

β = 0.6015 e = 0.665

ΔP	ṁ	T	Re/β	K	KC
2.500	1.640	80.000	.73016839E+05	.69303	.69182
3.000	1.791	80.000	.79714133E+05	.69068	.68615
3.500	1.923	80.000	.85594684E+05	.68661	.68184
4.000	1.998	80.000	.88943331E+05	.66739	.67968
4.500	2.153	80.500	.96385714E+05	.67776	.67561
5.000	2.246	80.500	.10057639E+06	.67094	.67377
5.500	2.338	80.500	.10468490E+06	.66584	.67228
6.000	2.457	80.000	.10936190E+06	.67002	.67097
6.500	2.571	80.000	.11442571E+06	.67354	.67000
7.000	2.672	80.500	.11963989E+06	.67452	.66950
7.500	2.756	80.500	.12341972E+06	.67224	.66945
8.000	2.841	80.500	.12719956E+06	.67083	.66966
8.500	2.933	80.000	.13051555E+06	.67182	.67007
9.000	3.013	80.500	.13492356E+06	.67087	.67092
9.500	3.089	80.500	.13829254E+06	.66928	.67181
10.000	3.193	80.500	.14297625E+06	.67443	.67340
10.500	3.270	80.500	.14642739E+06	.67406	.67483
11.000	3.349	80.500	.14996072E+06	.67445	.67653

β = 0.6015 e = 0.750

ΔP	$\dot{m}$	T	Re/β	K	KC
2.500	1.617	81.000	.72828899E+05	.68295	.68401
3.000	1.774	80.500	.79458641E+05	.68431	.68100
3.500	1.901	81.500	.86155960E+05	.67875	.67827
4.000	2.013	81.500	.91228849E+05	.67230	.67641
4.500	2.145	81.500	.97216517E+05	.67545	.67446
5.000	2.255	82.000	.10281575E+06	.67368	.67286
5.500	2.351	82.000	.10716598E+06	.66950	.67177
6.000	2.450	81.500	.11102143E+06	.66802	.67091
6.500	2.567	82.000	.11703763E+06	.67258	.66979
7.000	2.659	82.000	.12122053E+06	.67128	.66916
7.500	2.751	82.000	.12540343E+06	.67090	.66866
8.000	2.845	82.000	.12967000E+06	.67169	.66827
8.500	2.914	82.000	.13284900E+06	.66761	.66806
9.000	2.991	80.000	.13312913E+06	.66596	.66805
9.500	3.065	80.000	.13639610E+06	.66411	.66792
10.000	3.157	80.000	.14047982E+06	.66667	.66786
10.500	3.245	80.000	.14440019E+06	.66876	.66792
11.000	3.322	80.000	.14783051E+06	.66891	.66806

β = 0.6015 e = 1.0

ΔP	$\dot{m}$	T	Re/β	K	KC
2.500	1.642	79.500	.72654686E+05	.69381	.69301
3.000	1.789	79.500	.79148960E+05	.68997	.68951
3.500	1.919	79.500	.84912628E+05	.68530	.68680
4.000	2.046	79.500	.90513940E+05	.68333	.68451
4.500	2.175	79.500	.96196428E+05	.68469	.68255
5.000	2.285	79.500	.10106713E+06	.68245	.68115
5.500	2.373	79.500	.10496369E+06	.67577	.68022
6.000	2.487	79.500	.10999676E+06	.67803	.67927
6.500	2.606	79.500	.11527335E+06	.68268	.67857
7.000	2.701	79.000	.11876470E+06	.68194	.67828
7.500	2.764	79.000	.12150791E+06	.67403	.67814
8.000	2.881	79.000	.12667159E+06	.68036	.67811
8.500	2.942	79.000	.12933412E+06	.67392	.67822
9.000	3.065	78.000	.13308390E+06	.68231	.67849
9.500	3.120	78.000	.13547463E+06	.67604	.67875
10.000	3.230	79.500	.14287402E+06	.68218	.67994
10.500	3.303	79.500	.14612115E+06	.68087	.68066
11.000	3.377	79.500	.14936829E+06	.68000	.68149

VITA

The author was born May 2, 1943 in Litchfield, Illinois. His entire childhood was spent in Mt. Olive, Illinois, where he received his primary and secondary education. He graduated from Mt. Olive High School in May, 1961.

He entered the Missouri School of Mines and Metallurgy in September, 1961 and graduated in May, 1965 from the University of Missouri at Rolla with the degree of Bachelor of Science in Mechanical Engineering. Since September, 1965 the author has been pursuing a program leading to a degree of Master of Science in Mechanical Engineering while working as a graduate assistant.

In June, 1965 he married the former Sharra Ann Ebert.

His society memberships include Society of Automotive Engineers, American Society of Mechanical Engineers, and Pi Tau Sigma and Tau Beta Pi National Honorary Fraternities.