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Quarterly Progress Report #7, NAS8-11297
STUDY OF PRESSURE LOSSES IN TUBING AND FITTINGS

Period Covered: December, 1965, January, February, 1966

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TABLE OF CONTENTS

page

LIST OF FIGURES

INTRODUCTION

The objectives of this study are to develop an analytical method for predicting the behavior of the flow through tubing-fitting systems for steady-state and transient flow conditions; to obtain experimental evaluation of the pressure losses in flow systems such as those encountered in modern rockets, to include flexible connectors primarily; and to correlate the results of the analytical predictions with the experimental observations.

As described in the Interim Report, 1965, a correlation equation has been developed and an experimental system has been constructed from which data on losses in flexible connectors has been collected.

During this report period, primary effort has been directed at extending the literature review, refinement of the flow systems analysis in order to gain better agreement between prediction and observation, and the study of entrance effects in flexible metal hoses.

ANALYTICAL CONSIDERATIONS

A. Flow Losses in Flexible Metal Hose

The correlation equation which was presented in Quarterly Progress Report No. 5 remains as the best analytical representation of the data obtained to date. Efforts will be made during the next quarter to improve the agreement of a correlation equation with the data which has been collected at Mississippi State University.

B. System Analysis

The computer program to predict the pressure drop in an arbitrary flow system has been modified during the report period to incorporate pressure drop relations obtained from reference [1]. Those relations determine the pressure differential across abrupt contractions and expansions and are based upon total and static pressure ratios rather than on a loss coefficient. Benedict *et al* [1] give equations predicting the pressure differential more accurately for compressible flow than does the use of a loss coefficient based on incompressible flow.

Having modified the program, an analysis was performed on a section of the test line to determine its pressure drop characteristics. The section of line considered is shown schematicly in Figure 1 and incorporates most of the components that have been considered in the analysis. The results of the analysis are given in Figure 2 which presents the predicted pressure drop through the line as a function of mass flowrate. It should be noted that the 1 inch diameter, 10 feet long flexible metal hose in the line produces the major pressure drop; approximately 87% of the total drop at a mass flow rate of 0.3 lbm/sec.

To ascertain the accuracy of the predicted pressure drop, experimentation was performed on the test line described above. The pressure drop was obtained from a 10 ft. mercury manometer. Volumetric flowrates were obtained from the Cox turbine flowmeter. This was then converted to mass flow rate. The experimatal data thus determined are also presented in Figure 2 which is a comparison of the predicted pressure drop with this data. As can be seen from the Figure 2, the predicted pressure drop agrees closely with the measured pressure drop except at very low flowrates, where the error is approximately 25%. At higher flowrates, greater than 0.1 lbm/sec, the error is on the order of 4-5%.

In order to analyze the entire system, it was required that the pressure loss characteristics of the pressure regulator be determined. As a pressure regulator will have an indefinite number of loss coefficients depending upon the pressure setting, it was decided that loss characteristics would be determined with the regulator set at its maximum setting, i. e., fully opened. Under these conditions, a loss coefficient, K, was determined from

$$K = \frac{\Delta P}{v^2/2gc}$$

where:

ΔP is the pressure drop in lb/ft^2

P is the density in lbm/ft^3

v is the fluid velocity in ft/sec^2

The data obtained are presented in Figure 3 as a function of Reynolds number based on the pipe diameter. The correlation equation for this data, which will be used in the system analysis, is given as

$$K = 3.65 \times 10^{11} \, Re_D^{-1.84} ; \; 2 \times 10^4 \leq Re \leq 2 \times 10^5$$

During the report period, blowdown tests were begun which will be used to verify the flow system predictions obtained from the computer solution.

The test consisted of allowing the 2000 ft^3 storage vessel to vent down from a high initial pressure while recording the pressure and temperature. These curves are presented in Figure 4.

The primary purpose of the initial test was to determine the polytropic exponent to be used to relate temperature to pressure in the tank during venting. It was found that this exponent was approximately 1.04.

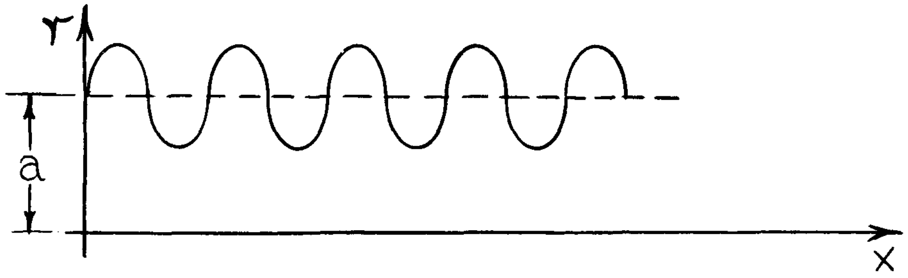
Currently additional instrumentation is being installed to record the flow rates during venting on strip charts rather than obtaining them as a digital read out.

C. Review of Flow Over a Rough Surface.

The first of several items considered during this report period was an investigation of the possibility of using momentum integral techniques. The question posed was whether or not such techniques applied to a flow with a convoluted boundary might predict the increase in friction factor which has been found. If one writes the r-momentum equation for turbulent pipe flow under the assumption of rotational symmetry in the time mean properties and steady mean flow the equation becomes

$$\frac{1}{\rho}\frac{\partial \bar{P}}{\partial r} = -\frac{1}{r}\frac{d}{dr}\left(r\,\overline{u_r^2}\right) + \frac{\overline{u_\phi^2}}{r} \quad .$$

using the notation shown below



and assuming a sinusoidal shape for the convoluted tube, an integration can be indicated yielding

$$\frac{1}{\rho}\int_{r\,=\,0}^{r\,=\,a\,+\,\sin x} \frac{\partial \bar{P}}{\partial r}\, dr + \int_{r\,=\,0}^{r\,=\,a\,+\,\sin x} \frac{1}{r}\, d\,(r\,\overline{u_r^2}) = \int_{r\,=\,0}^{r\,=\,a\,+\,\sin x} \frac{\overline{u_\phi^2}}{r}\, dr\ .$$

The properties and predictions of this equation were investigated and no results were immediately found to indicate the validity of the approach. It is felt that the idea does have merit and further study will be afforded the technique.

A thorough study was made during this reporting period of a recent Ph.D. dissertation on the subject of "Flow over a Rough Surface" by H. W. Townes [2]. Townes made extensive measurements of velocity distributions of the flow of water over transverse square cavities. Although the flow was of the open channel type, the results were applicable here especially for the many photographs of the flow. Excellent results of a dye method of flow visualization were of value since the study concentrated on the region of interaction between the cavity flow and mainstream flow. This study coupled with further study of

Laufer's work [3] prompted consideration of the significant dimensionless groups involved in the problem. It was felt that the characteristic length dimension to describe the surface roughness should be reconsidered. The average roughness height, as used by Nikuradse is not appropriate for convoluted tubing. As another possible characteristic surface dimension, the ratio of the convolutions' volume to surface area, was studied. This parameter may be written as

$$E_v/a \simeq \frac{1}{4}\left[\frac{2 + E/D}{1/E + 1/D + 2/5 + E/SD}\right] .$$

Preliminary indications are that this length would be satisfactory but no significant advantage would be gained by its use.

Possibly a more reasonable choice of a non-dimensional quantity to characterize the surface roughness is to be found with dimensional analysis. Assuming the pertinent variables to be T_w, ρ, ν, and some geometric length such an analysis will predict the following significant dimensionless number

$$E^* = \frac{EV_T}{\nu} ,$$

where V_T is the shear velocity defined by $V_T = \frac{T_w}{\rho}$, or $V_T = -\nu \left.\frac{\partial V}{\partial r}\right)_{\text{wall}}$.

The detailed experiments performed by Laufer led him to the conclusion that in the close proximity of the wall "using the similarity parameters V_T and ν/V_T the flow field in this region was shown to be independent of the Reynolds number" number" [3] . In this case the characteristic length is the ratio ν/V_T.

It seems only reasonable, however, that the quantity used to characterize the roughness elements be in some way related to some characteristic dimension of the mainstream turbulent flow. Such a quantity is to be found in what Hinze [4] calls the micro scale or dissipation scale of turbulence.

With the above definitions of a characteristic dimension of surface configuration to choose from,the selection is by no means obvious. However, it is felt that the latter course offers the most reasonable choice. The advantage to be gained by incorporating the micro scale of the mainstream turbulence is to be investigated during the next reporting period.

EXPERIMENTAL

A. Data Acquisition

Experimental efforts included system blowdown type studies as well as studies on the entrance effects in the flexible metal hose. The results of these studies are presented below.

B. Entrance Effects

The entrance effects test section as described in Quarterly Progress Report No. 6 was used in obtaining the test results discussed below. The temperature, flowmeter reading, and various pressure readings were made and recorded as previously reported. Additionally, twelve pressure differences are observed and recorded along the length of the hose relative to the hose entrance pressure. The axial location of these points are logarithmically distributed from the entrance.

From this information, in addition to the Reynolds number and friction factor for the entire length of hose, the friction factor between the hose entrance and any of the various downstream pressure taps may be calculated.

A computer program has been prepared for the IBM 1620 in FORTRAN to accomplish this reduction and is presented in Appendix A.

The results of preliminary studies indicate that the friction factor had an appreciable variation only in the upstream 1½ feet of the hose at Reynolds numbers of 0.466×10^5 and at 0.576×10^5. However, as the Reynolds number was increased, there was a variation throughout the hose length and at higher Reynolds numbers - greater than 0.165×10^6 - a manifestion of exit effects appeared. The results of these studies are presented as Figure 5.

CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Progress toward accomplishment of the stated objectives has been made but no technical conclusions need be iterated at this time. These will be expounded in the second Interim Report to be submitted in June, 1966.

B. Recommentations

It is recommended that continued emphasis be placed on the system analysis and the experimental effort to ascertain the flow characteristics in flexible metal hose of various configurations.

Additional effort should be directed toward internal localized velocity measurements in order to arrive at some possible design criteria which might lead to more efficient configurations relative to flow losses.

Expanded effort in the direction of fluid transients would benefit the study of the Pogo Effect on liquid rockets. This would be primarily an analytical effort to establish a generalized system of equations which would accommodate various geometrical configurations and entrance conditions in order to establish the behavior of fluid transients in the fuel and oxidant lines in the rockets.

LIST OF REFERENCES

1. Benedict, R. P., Carlucci, N. A., and Swetz, S. D., "Flow Losses in Abrupt Enlargements and Contractions" Journal of Engineering for Power, Trans. ASME, Vol. 88, January 1966. p 73.

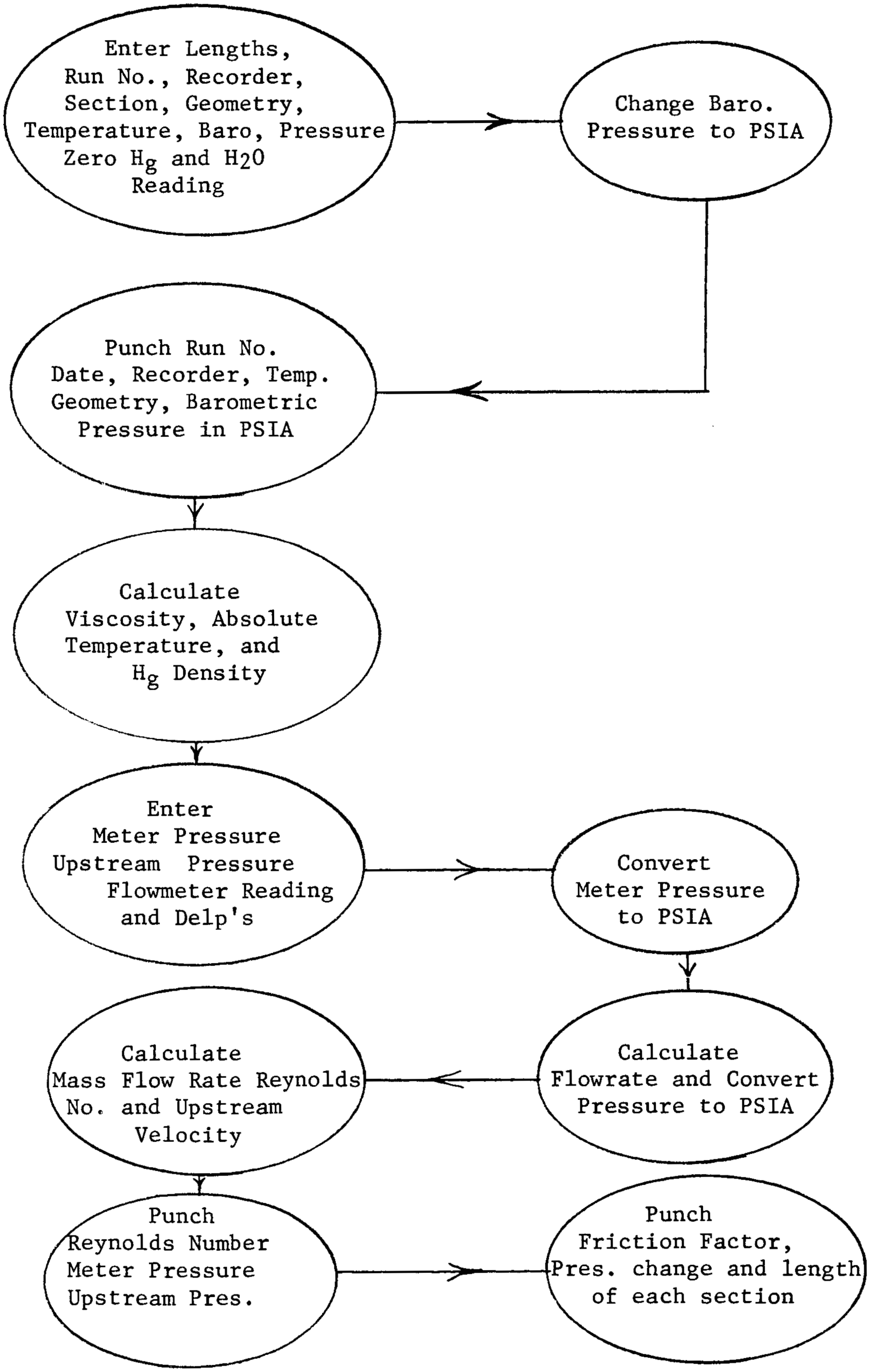
2. Townes, H. W. 1965. Flow Over a Rough Surface. Ph.D. Dissertation - California Institute of Technology.

3. Laufer, J. 1954. The Structure of Turbulence in Fully Developed Pipe Flow. NACA TR 1174.

4. Hinze, J. O. 1959. Turbulence. An Introduction to its Mechanism and Theory. McGraw-Hill, New York.

Appendix A

FLOW DIAGRAM FOR ENTRANCE EFFECT PROGRAM



```
C  ENTRANCE EFFECT STUDY
      DIMENSION DELP(12), XL(12), F(12)
C  ENTER LENGTHS
      N=12
      DO 89 I=1,N
      READ 25, XL(I)
   25 FORMAT(F10.5)
      XL(I)=XL(I)/12.0
   89 CONTINUE
         WAT=0.03613
         GC=32.172
         PI=3.14159
  100 READ 1,IRUN,DT1,DT2,REC,SEC
    1 FORMAT(I3,A5,A2,A3,A3)
      READ 30,DATA,W1,W2,W3,DIAT,R,DR,P
   30 FORMAT(A3,A5,A5,A5,F5.3,F8.4,2F7.4)
   81 CONTINUE
      READ 306,TEMP,BARP,ZERO,ZEROW
  306 FORMAT(4F10.5)
         BARP=BARP*0.4912
      PUNCH 3,IRUN,DT1,DT2,REC
    3 FORMAT(5H RUN ,I3,5X,5HDATE ,A5,A2,5X,12HRECORDED BY ,A3,//)
      PUNCH 4,SEC,W1,W2,W3,DIAT,TEMP
    4 FORMAT(1H ,A3,3A5,F6.2,5X,14HTEMPERATURE = F5.1)
      PUNCH 5,BARP
    5 FORMAT(1H ,22HBAROMETRIC PRESSURE = F6.2,5H PSIA///)
         XMU=EXPF(-11.4227+0.001494791*TEMP)
         DIAT=DIAT/12.0
         ALPHA=0.18182E-03
         BETA=0.0078E-06
         T=(5.0/9.0)*(TEMP-32.0)
         VOL=848.8*(1.0+ALPHA*T+BETA*T*T)
         HG=VOL/1728.0
    6 READ  13,PMETE,PUP,ICHAN,ICPS
   13 FORMAT(2F10.5,2I5)
      IF(PMETE)308,315,308
  315 CONTINUE
      GO TO 100
  308 CONTINUE
C  ENTER PRESSURE CHANGE, DELP
      DO 99  I=1,N
      READ 310, DELP(I)
  310 FORMAT(F10.5)
   99 CONTINUE
         PMETE=(PMETE-ZERO)*2.0*HG
         CPS=ICPS
```

```
C          CHANNEL 1    CPS = 25.0*CFM
C          CHANNEL 2  CPS = 3.0*CFM
      GO TO(619,620,621,622),ICHAN
  619    CFM=CPS/25.0
      GO TO 623
  620    CFM=CPS/3.0
  623    PUP=(PUP-ZERO)*2.0*HG
      DO 8  I=1,N
         DELP(I)=(DELP(I)-ZERO)*2.0*HG
         DELP(I)=ABSF(DELP(I))
    8 CONTINUE
      GO TO 624
  621    CFM=CPS/25.0
      GO TO 626
  622    CFM=CPS/3.0
  626    PUP=(PUP-ZEROW)*2.0*WAT
      DO 11  I=1,N
         DELP(I)=(DELP(I)-ZEROW)*2.0*WAT
         DELP(I)=ABSF(DELP(I))
   11 CONTINUE
  624 CONTINUE
         PMETE=ABSF(PMETE)
         PUP=ABSF(PUP)
         RHOAT=(144.0/53.3)*BARP/(TEMP+460.0)
         RHOUP=RHOAT*(PUP+BARP)/BARP
         XLBSM=CFM*RHOAT*(PMETE+BARP)/BARP
         XLBSE=XLBSM/60.0
         VUP=XLBSE/(RHOUP*PI*DIAT*DIAT/4.0)
         REYUP=RHOUP*VUP*DIAT/XMU
      DO 12  I=1,N
         F(I)=2.0*DELP(I)*144.0*DIAT*GC/(XL(I)*RHOUP*VUP*VUP)
      IF(I-1) 77,78,77
   78 PUNCH 101, REYUP
  101 FORMAT(2X,11HREYNOLDS = E10.3/)
   79 PUNCH 102, PMETE
  102 FORMAT(2X,11HPMETER   = F6.3,5H PSIA/)
   80 PUNCH 103, PUP
  103 FORMAT(2X,11HPRESUP   = F6.3,5H PSIA/)
      PUNCH 111, XLBSE
  111 FORMAT(2X,11HMASSFLO  = F6.3,5H LB/S//)
  142 PUNCH 150
  150 FORMAT(7HSECTION,3X,7HFFACTOR,4X,6HDELTAP,4X,6HLENGTH//)
   77 CONTINUE
  143 PUNCH 187, I,F(I),DELP(I),XL(I)
  187 FORMAT(I7,3F10.5)
      IF(I-12) 12,7,12
    7 PUNCH 9
    9 FORMAT(///)
   12 CONTINUE
      GO TO 6
      END
```

```
RUN 200      DATE 2/23/66      RECORDED BY JHM
 F8    FLEXONICS       1.00    TEMPERATURE =   66.0
BARОMETRIC PRESSURE =   14.65 PSIA


 REYNOLDS =   0.466E+05
 PMETER   =   1.109 PSIA
 PRESUP   =    .621 PSIA
 MASSFLO  =    .037 LB/S

SECTION    FFACTOR     DELTAP     LENGTH

      1     .09760     .02529      .34375
      2     .06766     .03613      .70833
      3     .09416     .07949     1.11979
      4     .08734     .10116     1.53646
      5     .08598     .13368     2.06250
      6     .08747     .17342     2.63021
      7     .08614     .21678     3.33854
      8     .08606     .27098     4.17708
      9     .08573     .33962     5.25521
     10     .08483     .37937     5.93229
     11     .08449     .43356     6.80729
     12     .08320     .59253     9.44792


 REYNOLDS =   0.576E+05
 PMETER   =   1.664 PSIA
 PRESUP   =    .932 PSIA
 MASSFLO  =    .046 LB/S

SECTION    FFACTOR     DELTAP     LENGTH

      1     .11188     .04336      .34375
      2     .09954     .07949      .70833
      3     .09159     .11562     1.11979
      4     .09178     .15897     1.53646
      5     .09013     .20955     2.06250
      6     .09017     .26736     2.63021
      7     .09024     .33962     3.33854
      8     .08900     .41911     4.17708
      9     .08782     .52027     5.25521
     10     .08752     .58531     5.93229
     11     .08569     .65757     6.80729
     12     .08345     .88880     9.44792
```

```
  REYNOLDS =  0.866E+05
  PMETER   =  3.265 PSIA
  PRESUP   =  2.773 PSIA
  MASSFLO  =   .068 LB/S

SECTION   FFACTOR    DELTAP    LENGTH

      1    .15703    .12322    .34375
      2    .11431    .18483    .70833
      3    .16872    .43128   1.11979
      4    .15810    .55450   1.53646
      5    .15703    .73934   2.06250
      6    .15392    .92417   2.63021
      7    .15360   1.17062   3.33854
      8    .14861   1.41706   4.17708
      9    .14894   1.78673   5.25521
     10    .14104   1.90996   5.93229
     11    .13877   2.15640   6.80729
     12    .12284   2.64929   9.44792


  REYNOLDS =  0.165E+06
  PMETER   = 12.630 PSIA
  PRESUP   = 11.521 PSIA
  MASSFLO  =   .131 LB/S

SECTION   FFACTOR    DELTAP    LENGTH

      1    .16180    .30806    .34375
      2    .14133    .55450    .70833
      3    .12914    .80095   1.11979
      4    .13756   1.17062   1.53646
      5    .14562   1.66351   2.06250
      6    .14802   2.15640   2.63021
      7    .15660   2.89574   3.33854
      8    .16777   3.88152   4.17708
      9    .18415   5.36020   5.25521
     10    .18938   6.22276   5.93229
     11    .19445   7.33177   6.80729
     12    .21310  11.15168   9.44792
```

```
  REYNOLDS =  0.233E+06
  PMETER   = 23.351 PSIA
  PRESUP   = 22.119 PSIA
  MASSFLO  =   .184 LB/S

SECTION   FFACTOR    DELTAP     LENGTH

     1     .25169      .67773     .34375
     2     .18877     1.04740     .70833
     3     .18965     1.66351    1.11979
     4     .18941     2.27963    1.53646
     5     .19449     3.14219    2.06250
     6     .20036     4.12797    2.63021
     7     .20497     5.36020    3.33854
     8     .20148     6.59243    4.17708
     9     .20205     8.31755    5.25521
    10     .20551     9.54978    5.93229
    11     .21607    11.52135    6.80729
    12     .28555    21.13274    9.44792


  REYNOLDS =  0.299E+06
  PMETER   = 34.934 PSIA
  PRESUP   = 32.962 PSIA
  MASSFLO  =   .236 LB/S

SECTION   FFACTOR    DELTAP     LENGTH

     1     .27051      .92417     .34375
     2     .20129     1.41706     .70833
     3     .21590     2.40285    1.11979
     4     .20577     3.14219    1.53646
     5     .21340     4.37442    2.06250
     6     .20505     5.36020    2.63021
     7     .21353     7.08532    3.33854
     8     .21519     8.93367    4.17708
     9     .21587    11.27490    5.25521
    10     .22467    13.24647    5.93229
    11     .23222    15.71093    6.80729
    12     .33266    31.23703    9.44792
```

```
     REYNOLDS =  0.355E+06
     PMETER   = 44.545 PSIA
     PRESUP   = 42.081 PSIA
     MASSFLO  =   .280 LB/S

 SECTION   FFACTOR    DELTAP     LENGTH

      1     .28991    1.17062     .34375
      2     .19993    1.66351     .70833
      3     .21078    2.77252    1.11979
      4     .18775    3.38863    1.53646
      5     .22124    5.36020    2.06250
      6     .21337    6.59243    2.63021
      7     .21838    8.56400    3.33854
      8     .21974   10.78201    4.17708
      9     .22656   13.98581    5.25521
     10     .22899   15.95738    5.93229
     11     .24271   19.40762    6.80729
     12     .34808   38.63041    9.44792
```

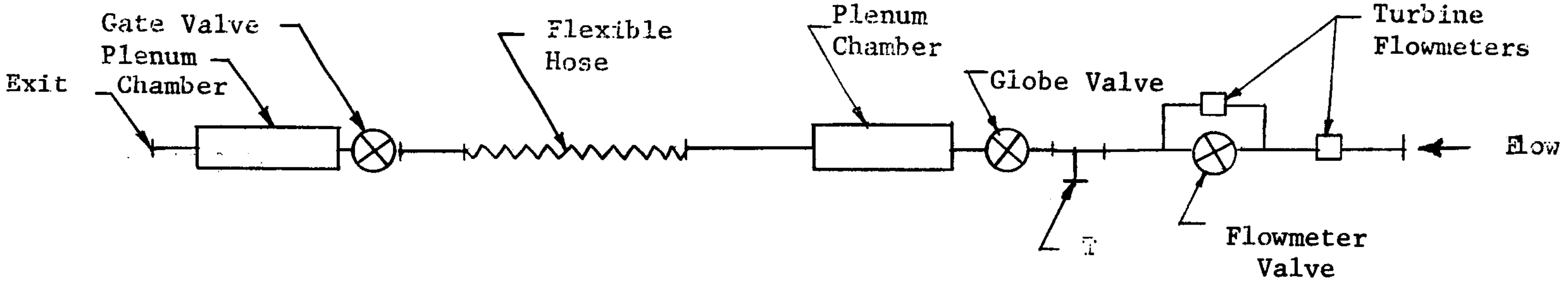


Figure 1. Schematic of Test System

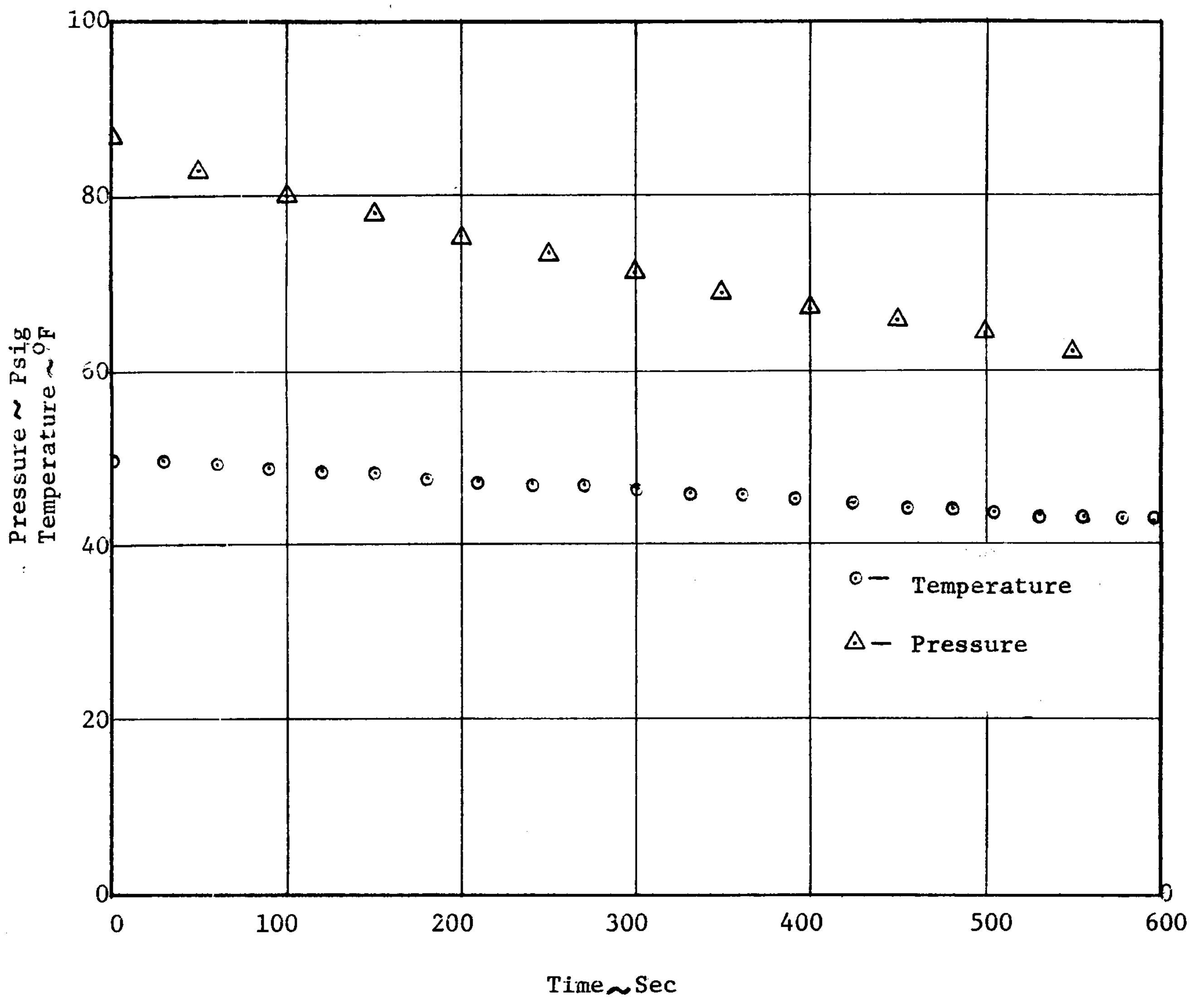


Figure 2. Pressure and Temperature History During Tank Venting.

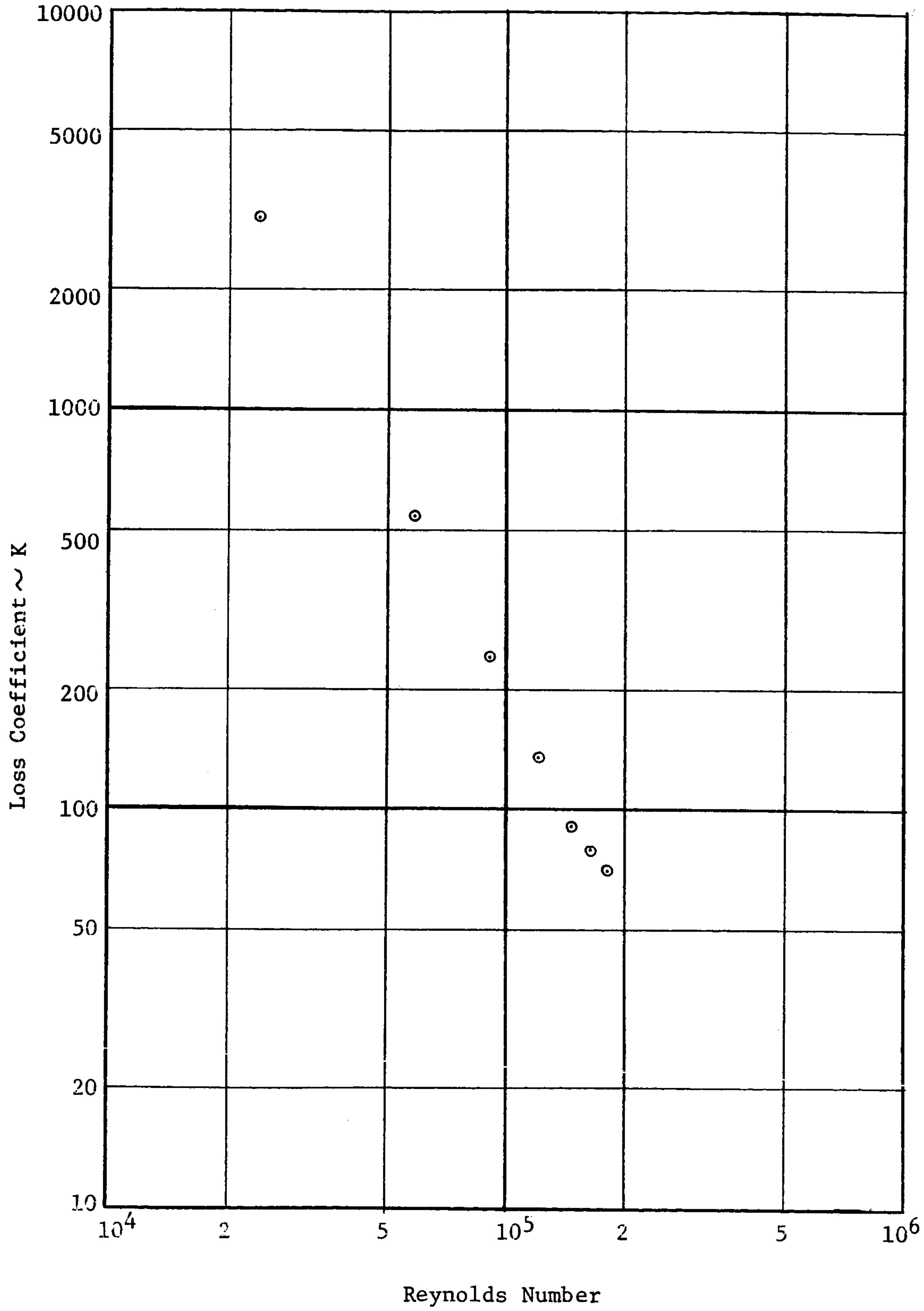


Figure 3. Loss Coefficient for Pressure Regulator Versus Reynolds Number

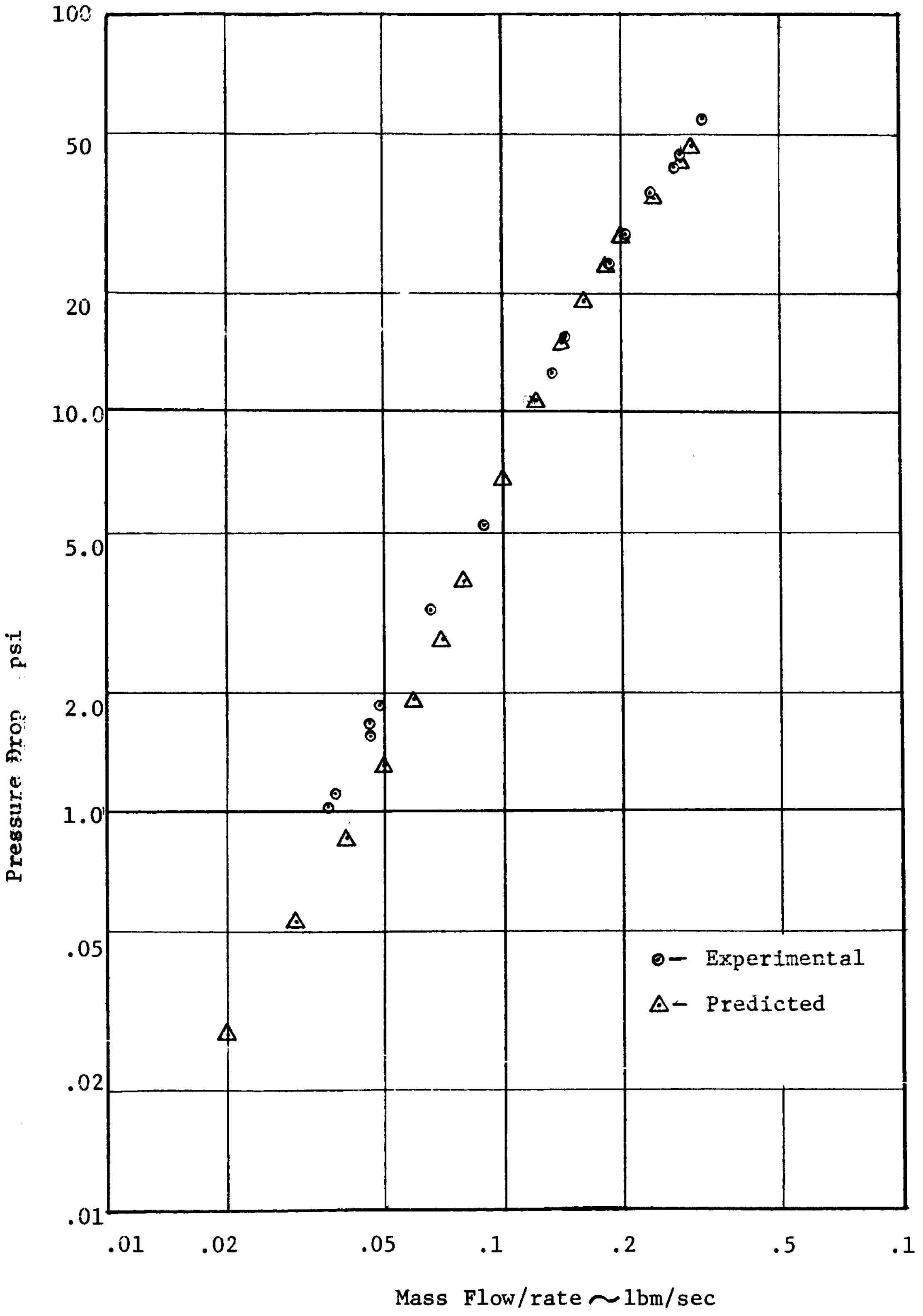


Figure 4. Comparison of Predicted Pressure Drop with Actual Pressure Drop

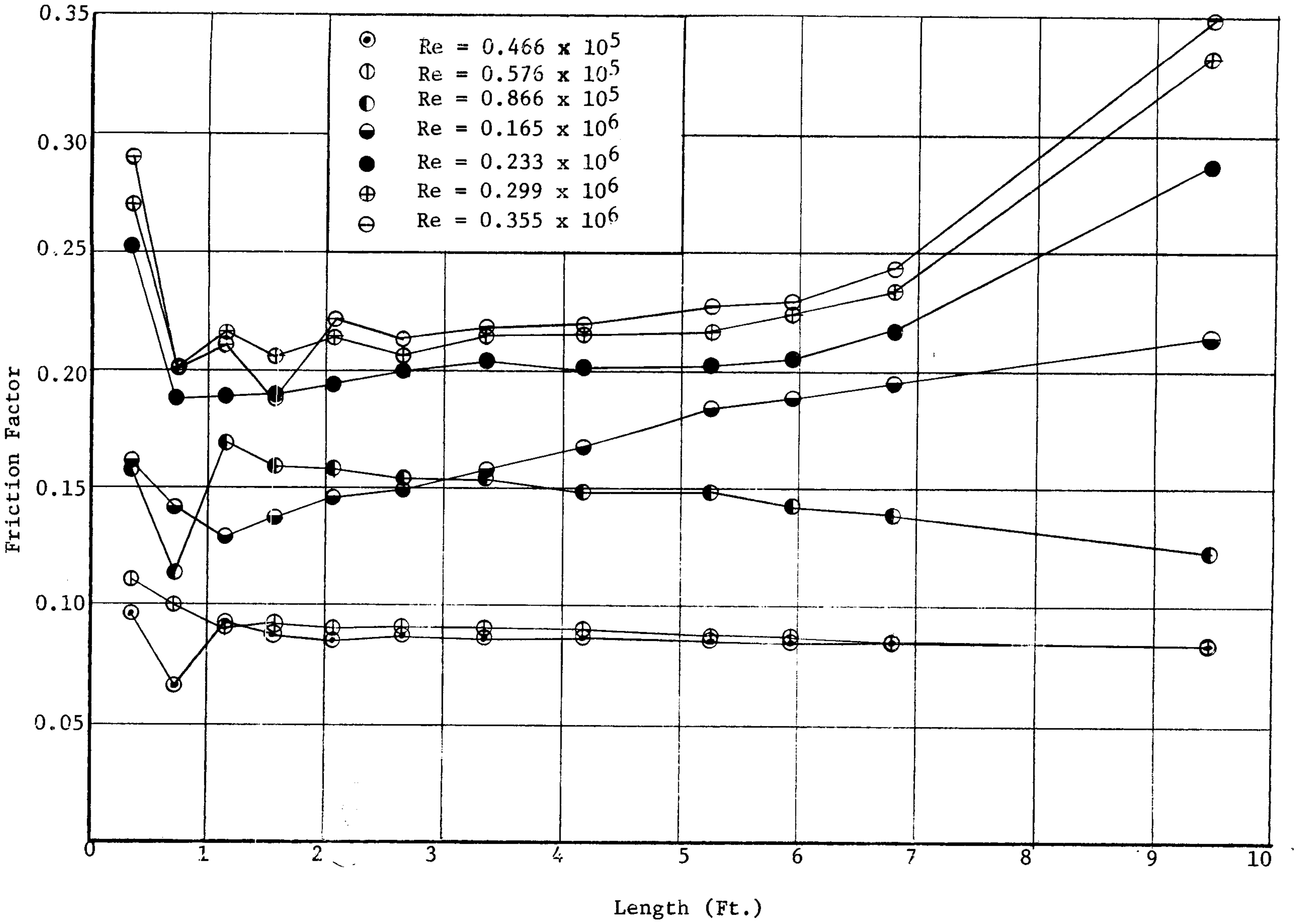


Figure 5. Entrance Effects Study on Flexonics 1 inch Diameter Hose