# Lehigh University Lehigh Preserve

Theses and Dissertations

1960

# Pressure drop in helically coiled tubes

Richard N. Meier *Lehigh University* 

Follow this and additional works at: https://preserve.lehigh.edu/etd Part of the <u>Chemical Engineering Commons</u>

### **Recommended** Citation

Meier, Richard N., "Pressure drop in helically coiled tubes" (1960). *Theses and Dissertations*. 5020. https://preserve.lehigh.edu/etd/5020

This Thesis is brought to you for free and open access by Lehigh Preserve. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of Lehigh Preserve. For more information, please contact preserve@lehigh.edu.

# PRESSURE DROP IN HELICALLY

# COILED TUBES

by

# Richard N. Meier

A THESIS

Presented to the Chemical Engineering Department

of Lehigh University

in Candidacy for the Degree of

Master of Science

# LEHIGH UNIVERSITY

1960

This Thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

Jan 21, 196/ Date

1. Miller .

Professor in Charge

Head of the Department

# ACKNOWLEDGMENT

The author wishes to express his gratitude to Dr. L. A. Wenzel and Dr. Peter K. Lashme t for their guidance during this investigation.

Neil Schwartz, Research and Development mechanic at Air Products, is thanked for his help in constructing various parts of the equipment.

Financial support for this project by Air Products, Incorporated, is very gratefully acknowledged.

ABSTRACT
INTRODUCTION
THEORETICAL BACKGROUND
EXPERIMENTAL BACKGROUND
TEST PROGRAM
TEST APPARATUS
TEST PROCEDURE
CALCULATION OF RESULTS
DISCUSSION OF RESULTS
CONCLUSIONS
LITERATURE CITED
APPENDIX
DATA OF MEIER
DATA OF LAPIN
SAMPLE CALCULATIONS

# TABLE OF CONTENTS

	Pa	se no.
••••••	•	1
	•	3
• • • • • • • • • • • • • • • • • • • •	••	5
	•	6
	•	12
	•	14
	•	20
	•	21
	•	22
	•	29
	•	30
	. 35	- 38
	39	- 40
		42

Dage No.

# LIST OF TABLES AND FIGURES

Figure 1	Fluid Flow in Coiled T
Figure 2	Effect of Curvature Ra Reynolds Number
Figure 3a	Test Equipment - App
Figure 3b	Test Equipment - Tes
Figure 3c	Test Equipment - Tes
Figure 3d	Test Equipment - Flo
Figure 4	Effect of Reynolds Nur Factor - Data of Meie
Figure 5	Effect of Reynolds Nur Factor - Data of Lapin
Figure 6	Effect of Curvature Ra - Laminar Region
Figure 7	Effect of Curvature Ra - Turbulent Region
Figure 8	Effect of Curvature R
Figure 9	Correlation for Press Tube - Laminar Regio
Figure 10	Suspected Data
Figure 11	Effect of Reynolds Nu for Straight Tube - D
Table 1	Summary of Experime Drop in Coiled Tubes

	Page No.
ſube	6
atio on Critical	8
oaratus	16
st Instruments	17
st Coil	18
w Diagram	19
mber on Friction er	25
mber on Friction n	26
atio on Friction Factor	27
atio on Friction Factor	28
atio on Friction Ratio	31
sure Drop in Coiled on	32
	33
mber on Friction Factor Diameter Determinations	34
ental Work for Pressure	11

# LIST OF TABLES AND FIGURES (cont'd)

Table 2	Meier Data - Straight
Table 3	Meier Data - 0.048 C
Table 4	Meier Data - 0.100 C
Table 5	Meier Data - 0.125 C
Table 6	Lapin Data - 0.030 C
Table 7	Lapin Data - 0. 135 C
Table 8	Cross Plot Data

Table

ht Tube	35
Coil	36
Coil	37
Coil	38
Coil	39
Coil	40
	41

# NOMENCLATURE

Α	Cross sectional area.
D <sub>c</sub>	Diameter of coil
Dt	Inside diameter of tube
f <sub>c</sub>	Fanning friction factor
$\mathbf{f}_{\mathbf{S}}$	Fanning friction factor
G	Mass velocity
g <sub>c</sub>	32.12 gravitational con
L	Length
N <sub>Re</sub>	Reynolds number
ΔP	Pressure drop
w	Mass flow rate
م	Density
'n	Viscosity
1	

A

 $(D_t/D_c \text{ curvature ratio})$ 

for coiled tube

for straight tube ( $f_s/f_c$  friction of ratio)

nstant

### ABSTRACT

Pressure drop in three helically coiled tubes with a tube to coil diameter ratio of 0.048", 0.100", and 0.125" respectively was investigated at Reynolds Numbers from 70 to 70,000 using nitrogen and helium. Thin walled 3/32''copper tubing was finned before coiling to avoid the usual flattening effects.

dependent of Reynolds Number for design purposes.

For estimation of pressure drop in coils,

$$f_s/f_c = \ln \left( \ln \left( \frac{12.0}{N_{Re} 0.2} \right) \right) - 0.13 \ln (D_t/D_c)$$
  
 $N_{Re} < 2100$ 

where  $f_s = 16/N_{Re}$ . In the turbulent region above Reynold's Numbers of 10,000

$$f_{\rm s}/f_{\rm c} = 1.08$$

-1-

The friction factor for straight tube was found to be lower than that for the corresponding coiled tube, the ratio of  $f_{\rm S}/f_{\rm C}\,$  approaching one at low Reynolds Numbers (Figure 4 ). The transition to turbulent flow occurred at Reynolds Numbers of 6000 to 10,000, after which the ratio  $f_s/f_c$  may be considered in-

- 4.17  $(D_t/D_c)$ 

 $N_{Re} \rightarrow D_{t}/D_{c} \rightarrow D_{t}/D_{c} \rightarrow 0.125 \qquad (M_{DG})^{0.32}$   $f_{s} = 0.0014 + 0.090 \qquad (M_{DG})^{0.27}$ pressure drop in coils, Figure 6 and Figure 7 provide For estimating design charts showing the effect of curvature on the friction factor ratio.

- 2 -

Incorrect

10,000 . 03

# INTRODUCTION

Coils of tube are chiefly used in connection with heating and refrigeration in order to transfer heat from one fluid to another. Since both the pressure required to obtain the necessary circulation and the heat transfer at that circulation rate are dependent upon the resistance to flow, it is important to have design charts or equations for estimating pressure drop in coils with various degrees of curvature.

While the relationships for pressure drop in straight tube have been thoroughly investigated and proven, the flow of a fluid in curved pipe follows a more complex path, even in the laminar region, and obtaining theoretical or empirical relationships is difficult. Secondary flow is imposed on the normal flow profile and the flow pattern becomes a three dimensional consideration. Furthermore, the degree of curvature is an additional variable to be considered in the final analysis.

These complexities have prevented integration of the equations of motion and have limited both the quantity and scope of the theoretical and experimental investigations.

Past research has been mainly concentrated in the turbulent region; the derived - 3 -

relationships, however, are inconsistent with one another and usually correlated only the data of the particular investigation. Little work has been done in the laminar region, and no investigator has considered both regions simultaneously.

The purpose of the research reported here was to investigate both regions of flow in coils with different degrees of curvature, and to develop a design correlation for each region of flow, consistent with both the data obtained and that of other experimentors.

# THEORETICAL BACKGROUND

The theoretical background is quite limited because of the difficulty in solving the equations of motion for expressions describing the flow behavior.

For a small degree of curvature, Dean (4) made certain assumptions as to the relative magnitude of the fluid velocities and, for a given pressure gradient in the laminar region of flow, obtained an expression for the ratio of velocities in a curved pipe to those in a straight pipe of equal cross section. He further developed an expression for the velocity at any point relative to the centerline velocity. Both of these solutions were experimentally verified by White (21), however, the limitation that only a small degree of curvature be considered makes the expressions of little value.

In the turbulent region above Reynolds Numbers of 150,000, Weske 🚧 derived a relation for the net pressure drop in curved ducts as a function of Reynolds Number and diameter ratio by integrating the equations of motion of the shedding layer, somewhat analogous to the 'buffer' layer in straight tube. For more details, see reference. He reports that experimental results support the assumptions he made in the development, however, quantitative information have developed theoretical is not available. A few others (1, 16)equations, but experimental results fail to verify their validity.

- 5 -

# EXPERIMENTAL BACKGROUND

The first significant results of experimental work on fluid flow inside coiled tube was reported by Eustice (8), who experimented with the injection of dye into water flowing in a glass U-tube. It was observed that fluid particles in the center of the pipe traveled to the outside wall as a result of the centrifugal force of the water rounding the bend. Once at the wall, the fluid split into two streams, each returning along one of the sides of the tube, thus introducing a circular motion of two longitudinal vortexes. The same was latter observed by Taylor(19), i.e. the fluid formed two helixes, symmetrically disposed with regard to the diameter through the coil axis and the tube (see Figure1). Hawes (3) characterized the flow in coils by three stable regions.

# Figure 1



Using a coil with a  $D_t/D_c$  ratio of 0.100, he found: (1) laminar flow below  $N_{Re}$ = 30; (2) Exceedingly stable double-helical type flow for 30 <  $N_{Re}$  < 8000; (3) Turbulence above  $N_{Re} = 8000$ .

The work of White (21) further verified the indications of increased stability of flow through coiled tube. Together with the results of Taylor (19) and Adler (1), White's values for critical Reynold's Number are shown on Figure 2.

White made a study of the laminar flow of water through coils with curvature ratios  $D_t/D_c$  equal to 0.066, 0.020, and .0005. White correlated his data plus that of Grindley and Gibson (II) by plotting  $f_c/f_s$  vs.  $N_{Re} \left(D_t/D_c\right)^{1/2}$  on log-log coordinates. The data fell on one curve and the relationship was given

$$f_{S}/f_{C} = 1 - \left(1 - \left(\frac{11.6}{K}\right)\right)$$
  
where  $K = N_{Re}(D_{t}/D_{c})^{1/2}$ 

to relate the friction factor ratios to the Reynolds Number and curvature ratio. White sets the limitation that 11.6 < K < 2000 and suggests for K < 11.6, the friction factor for straight tubes be used.

White (22) later did work in the turbulent region also, and proposed the relation

- 7 -

2.220.45



$$f_c = 0.08 N_{Re}^{-1/4} + 0.01$$

To express  $f_c$  Lorentz (16) proposed a similar equation

$$f_c = 0.08 N_{Re}^{-1/4} + 0.32$$

Lapin (15) conducted pressure drop measurements at higher Reynolds Numbers for air flowing inside coils made of 0.495" I.D. tube and having curvature ratios of 0.03 and 0.135. His data was not correlated at the time of the experimentation and is presented now with that of the author.

Christensen obtained data for the flow of three fluids (air, toluene, and water)(3) through three helical coils having curvature ratios of 0.049, 0.092, and 0.136 at Reynolds Numbers from 3 to 150,000. For his .049 and .092 coils, he proposed the correlation

$$f_c = 0.08 \text{ Re}^{-1/4} + 0.34 (D_t/D_c)^{-0.10} \frac{DG}{\mu}$$

He proposed another correlation for coils having curvature ratios greater than 0.092, since his smallest coil did not agree with his other two, however, the author believes the data for this particular tube to be in error since no other data, including that of the author, indicate that the friction factor is not a function of the curvature ratio at larger values of  $D_t/D_c$ .

- 9 -

2 
$$(D/D_c)^{1/2}$$
.

$$(D/D_c)^2$$

Finally, it should be mentioned that several comprehensive studies [Richter (18), Adler (1), Ito (14)] have been made using a curved pipe of one turn or less.

 
 Table 1
 is a summary of the experimental investigation of pressure drop
 in coiled tubing to include the work of the author.

- 10 -

# TABLE 1

# SUMMARY OF EXPERIMENTAL WORK FOR PRESSURE DROP IN COILED TUBES

Diameter of Pipe or Tube (inches)	Average Diameter of Coil (inches)	Curvature Ratio (D <sub>t</sub> /D <sub>c</sub> )	Range of Flow Reynolds Number	Fluids Used	Experimentor	Comparison With Results of this Investigation
0.125*	14.40*	0.009	25 to 1,400	Air	Grindley and Gibson	In agreement.
0.250*	12.50*	0.020	16 to 13,000	Water	White	In agreement with author at low Reynolds Numbers.
0.495	16.75	0.030	3,000 to 50,000	Air	Lapin	In agreement.
0.081	1.69	0.048	60 to 66,000	Nitrogen Helium	Meier	In agreement in laminar region.
••••	••••	0.049	3,000 to 100,000	Air Toluene Water	Christensen	In agreement
0.406*	6.15*	0.066	0.06 to 41,000	Oil Water	White	Not in agreement with White's later work in the turbulent region - not considered.
••••	• • • • •	0.092	6,000 to 100,000	Air Toluene Water	Christensen	In agreement.
*convert	ed from cm.					

(continued)

ī

# TABLE 1 (cont'd)

# SUMMARY OF EXPERIMENTAL WORK FOR PRESSURE DROP IN COILED TUBES

• •	Diameter of Pipe or Tube (inches)	Average Diameter of Coil (inches)	Curvature Ratio _(D <sub>t</sub> /D <sub>c</sub> )	Range of Flow Reynolds Numbers	Fluids Used	Experimentor	Comparison with Results of this Investigation
	0.081	0.806	0.100	60 to 76,000	Nitrogen Helium	Meier	In agreement.
	0.081	0.648	0.125	60 to 72,000	Nitrogen Helium	Meier	In agreement.
	0.495	3.68	0. 135	3,000 to 50,000	Air	Lapin	In agreement.
- lla -	••••	••••	0.136	4,000 to 100,000	Air Toluene Water	Christensen	Data for this coil not in agreement with Christensen's other data - not considered.
	••••		•••••	Turbulent region	••••	White	Original data unobtainable at time of this work.
:							
							. a
							·
. •							

.

# TEST PROGRAM

The test program was planned using one diameter of tubing for three coils of varying curvature ratio. The ratios were chosen so as to best supplement or verify existing data.

Only one tube diameter was used since the primary aim of the investigation was to study the effect of curvature ratio on pressure drop by varying the diameter of the coil. It was therefore desirable to eliminate any other sources of possible variation in the data.

The particular tube diameter used was chosen for several reasons. It is much smaller than that of other investigators and therefore strengthens the validity of any correlation obtained by incorporating their data in its formulation. It was geometrically convenient, since a large variation in curvature ratio could be obtained without necessitating the use of large and unwieldy test sections. Finally, it was particularly suitable for finning, a process by which flattening of the tube during coiling was kept to a minimum.

Both the laminar and turbulent region of flow were investigated since the data for each coil could be compared with that of investigators of both regions.

- 12 -

Compressed helium and nitrogen were chosen as test fluids since they were readily available, convenient to use, and suitable for the Reynolds numbers to be investigated.

- 13 -

### TEST APPARATUS

The apparatus can be seen in Figs. 3a,b,c. The flow diagram is shown in The gas from a compressed gas cylinder was throttled through Fig. 3d. a Hoke Regulator and entered a 51" straight calming section where the inlet temperature was measured. Located at the end of the calming section and the beginning of the test section was the inlet pressure tap. This tap was connected to an 18" Heiss 500 psi Pressure Gauge, subdivided in increments of 0.5 psi, and then to one side of a pressure drop manifold. To the other side of the manifold was connected the outlet pressure tap, located immediately after the test section. The manifold consisted of a 46" glass water manometer, a 36" mercury manometer, and a 0 to 100 psi Barton differential pressure gauge, subdivided in 1 pound increments. The outlet temperature of the gas was then measured, after which it passed through a Brooks rotameter and was vented.

When making a test section, the copper tubing was annealed and then finned. The finning was not soldered to the tube, but was held there by mechanical bond. This flexible circular support prevented flattening during coiling of the tube. To check this, a cross-section of finned tube from coil 0.125 examined under a microscope showed no signs of crimping from the finning and appeared to be in round.

- 14 -

After coiling a test section, a brass sleeve with a 3/32" hole was soldered to each of the ends. Through this a .030" hole was drilled into the tube, particular care being taken that the tube remained in round and that rough edges were smoothed. A modified Swagelok tee was then carefully soft soldered to the sleeve taking care that no solder block the hole. The calming tube was then butted up against the test section tube inside the sleeve, and the end of the sleeve soft soldered to the calming tube. Finally, connections were made with regular Swagelok fittings on 1/4" tubing.

- 15 -









11

tud j

· ....

# 

# TEST PROCEDURE

The gas valve was opened and the pressure regulator adjusted to the desired inlet pressure. With the throttling valve closed, the manometer was checked for zero. The gas was then throttled through the test section at different flow rates. After steady state conditions were attained, the inlet and outlet temperatures, the inlet pressure, the pressure drop, and the flow rate were recorded.

# CALCULATION OF RESULTS

The exact diameter of the tubing was determined by testing a typical length of straight tubing in the laminar region of flow and using the data obtained together with the formula

 $f_s = 16/N_{Re}$ 

to calculate the true diameter. This was necessary since the allowable tolerances of the die used in drawing a lot of tubing is significant with regard to the total diameter. The exact diameter determined in this manner was found to be 0.081" as compared to the nominal diameter of 0.078". This data is shown in Table 2 & Fig. 11.

The arithmetric average of the temperature and pressure between the inlet and outlet to the test section was used in determining the average density and viscosity of the fluid.

The flowrates were determined from a rotameter conversion chart which had been made for each gas from the data obtained by using a wet test meter.

A sample set of calculations is given in the appendix.

### DISCUSSION OF RESULTS

The tabular results are summarized in Tables 2 thru 7 in the appendix. These tabular results are shown graphically in Fig. 4 & 5.

As expected,  $f_c$  at a given Reynolds number is considerably above that for a corresponding straight tube, the difference being greater at the larger curvature ratios. With Reynolds number as a parameter, a plot (Fig. 8) of the ratio of these friction factors,  $f_{\rm S}/f_{\rm C},$  vs the curvature ratio  $D_t/D_{\rm C}$  represents straight lines with a slope of -0.3. Replotting the original data points as  $(D_t/D_c)^{0.\,3/2.\,303}({\rm e}^{f_S/f_c})$  vs  $N_{Re}$  on semi-logarithmic paper (Fig. 9), the data fall on a straight line with one exception. The data for coil 0.125 between a Reynolds number of 70 and 350 are not correlated. Upon rechecking the original data, it was noticed that the flowrates for these particular ten points were taken on a rotameter which, on the following run, was found to be cracked at the base. Since it was not possible to correct the data, it was shown separately in Fig. 10.

A cross-plot of the points from the curve in Fig. 9 resulted in the design chart for pressure drop in the laminar region of flow (Fig. 6).

- 22 -

As indicated in the  $f_c vs N_{Re}$  plot (Fig. 4), this graph shows that the coiling of straight tube does not alter the friction factor at low Reynolds numbers and small curvature ratios, the upper allowable limit of Reynolds number decreasing with increasing curvature ratio.

Once the influence of curvature takes effect, the difference in  $f_s$  and  $f_c$  increases steadily with increasing Reynolds number. The effect of increasing curvature ratio, however, is greatest at initial bending and becomes less as  $D_t/D_c$  values become larger. An abrupt change in trend takes place at Reynolds numbers close to 10,000. This is in agreement with other experimentors (1) (19 (2), who suggest that in this region the onset of turbulence takes place. For coils 0.048, 0.100, and 0.125, Fig. 4 indicates critical Reynolds numbers of approximately 7000, 8000, and 8200, respectively. This may be compared with Fig. 2. The data, then, are in agreement with the findings of Hawes (13): at low Reynolds numbers in the range of 10 to 10,000,  $f_s/f_c$  decreases and an exceedingly stable double-helical type of flow (Fig. 1) is present; at still higher Reynolds numbers, turbulent flow is present.

In the turbulent region, a plot of  $f_S/f_C vs D_t/D_C$  is essentially a straight line approaching  $f_S/f_C = 1$  asymptotically. At higher values of

- 23

 $D_t/D_c$ , the points for Reynolds numbers of 10,000 and 50,000 fall on oneanother, indicating little variation of  $f_s/f_c$  with  $N_{Re}$ . At lower values of curvature ratio, there is some difference in these points. This could be attributed to the fact that any error in the slopes of Fig. 4 & 5 would become increasingly noticeable with decreasing  $D_t/D_c$  values since  $f_c$  approaches  $f_s$ . Since the highest Reynolds number investigated was about 70,000, it is difficult to derive a correlation showing the effect of Reynolds number on  $f_s/f_c$ . The straight line through the points in Fig. 7, however, should represent values of  $f_s/f_c$  which, when used together with the Koo equation for pressure drop in straight tube, will represent friction loss in coils quite satisfactorily for design purposes.

- 24 -



. A.

- 1

EFFECT OF REYNOLDS NUMBER ON FRICTION FACTOR FIGURE 4

- 25 -





- 26



# FIGURE 6 EFFECT OF CURVATURE RATIO ON FRICTION FACTOR - LAMINAR REGION

- 27 -

# Dt/Dc- CURVATURE RATIO



# FIGURE 7 EFFECT OF CURVATURE RATIO ON FRICTION FACTOR - TURBULENT REGION

- 28-

# Dt/Dc - CURVATURE RATIO

# CONCLUSIONS

The friction factor in smooth helically coiled tubes is higher than that for a corresponding straight tube. The effect on the friction factor for a given increase in curvature is greatest at initial bending, becoming less at higher  $D_t/D_c$  values. At very low Reynolds numbers, the ratio  $f_S/f_C$  approaches a value of one. The Reynolds number below which  $f_S/f_C = 1$  is determined by the curvature ratio and varies inversely with this curvature ratio.

The onset of turbulence in coiled tube occurs at much higher Reynolds numbers than in corresponding straight tube, thereby indicating the exsistance of a more stable type of flow. In the truly turbulent region, the ratio  $f_{\rm S}/f_{\rm C}\,$  may be considered independent of  $\,N_{{\rm R}e}^{}\,$  without serious error.

For design purposes, the curves in Fig. 6 may be used to estimate pressure drop in coiled tube in the laminar region of flow. In the turbulent region, Fig.7 together with the Koo equation for flow in straight tubes may be used.

- 29 -

10.0

# BIBLIOGRAPHY

1.	Adler, M., Z. angew Math. Mech
2.	Berg, R.R., and C.F. Bonilla, 7 (1950).
3.	Christensen, J.J., Jr., Ph.D. T. Carnegie Institute of Technology
4.	Dean, W.R., Phil. Mag., 3, 912
5.	Dean, W.R., Phil. Mag., 4, 208
6.	Dean, W.R., Phil. Mag., 5, 673
7.	Dean, W.R., Proc. Roy. Soc. (1
8.	Eustice, J., Proc. Roy. Soc. (L
9.	Eustice, J., Proc. Roy. Soc. (1
10.	Eustice, J., Eng., 120, 604-605
11.	Grindley, J.H., and A.H. Gibso
12.	"Handbook of Chemistry and Phy Publishing Co., 1953.
13.	Hawes, W.B., Trans. Inst. Che
14.	Ito, H., Transactions of the ASI (1959).
15.	Lapin, A., Air Products Resear Products, Inc., Allentown, Pa.
16.	Lorenz, H., Phys. Z., 30, 228
<b>17.</b>	Perry, J.H., "Chemical Engine Hill, New York, 1950.

- 30 -

- ch., 14, 257-276 (1934) Trans. N. Y. Aca. Sci., 13, 12-15
- hesis in Chemical Engineering, (1958).
- -924 (1927).
- (1927).
- (1928).
- London), A 121, 402-420 (1928).
- London), A 84, 107-118 (1910).
- London), A 85, 119-131 (1911).
- (1925).
- on, Proc. Roy. Soc., A 80, 114 (1908).
- vsics", 35th ed., Chemical Rubber
- em. Eng. (London), 10, 161-167 (1932). ME, 81, Series D, No. 2, 123-134
- rch Notebook No. 25 (1956), Air
- (1929).
- eer's Handbook", 3rd ed., McGraw-

# BIBLIOGRAPHY (cont'd)

18.	Richter, H., Z. Ver. deut. Ing., 74, 1757-1758 (1930); For Ver. deut.Ing., No. 338 (1930).
19.	Taylor, G.I., Proc. Royal Soc. (London), A 124, 243 (1929
20.	Weske, J.R., J. Appl. Mech., 15, 344-348 (1948).
21.	White, C.M., Proc. Roy. Soc. (London), A 123, 645 (1929)
22.	White, C.M., Trans. Inst. Chem. Eng., 10, 66-80 (1932).

- 30a -

, 74, 1757-1758 (1930); Forsch.

(London), A 124, 243 (1929).

(London), A 123, 645 (1929).



# FIGURE 8 EFFECT OF CURVATURE RATIO ON FRICTION FACTOR RATIO

1

# D<sub>t</sub>/D<sub>c</sub> - CURVATURE RATIO



### (p<sup>+</sup>/p<sup>0.3</sup>) X X X X X E X 11 1.0 ┽╁╀┼┨┼╧┼┊┨ 111 1 | | | | | | | | 111 TIT 1000 100 N<sub>Re</sub> - REYNOLDS NUMBER CORRELATION FOR PRESSURE FIGURE 9 DROP IN COILED TUBE - LAMINAR REGION

1



FIGURE IO SUSPECTED DATA POINTS

# N<sub>Re</sub> - REYNOLDS NUMBER



+++	<u>i I</u>	ţ	4	-	-	Ð	-	ŦĪ	-	-			-	H	-ŀ	H	Π	ŀ	1		Į.			T	-1-	Π	ŢĮ,		+	TT	T	T
	Щŀ	ļ	-	ŧ						D	Â	1	1	Δ		Ô	F		A	Ā	F	Ī	F	R		-	منعو				1	1:
Щ		Li.	-	E			_			_			-	-		-	-	-			-	-	<u> </u>								Γ	
卄	llŀ	lh	-	<u>+-</u>		C	)		S	57	٢I	R	A	.1(	G	1	1	Γ	•	T	L	][	3E	-	C	1	1	ſ.	Δ		1	ti.
11	I	11	-	-	-		:ŀ		-	÷	1	- -	j:		ī	1	H	H	Ľ	ij	ij.	•	, Li	-i	цī.	ġ	ii.	1		1:	H	+-
Ħ	ili	11	1-	-			-	+	-1	-			+	_   .   -   .	-		11	2	li	<u>;;</u>	+	11				4		_	:,	<u> </u> :	Ŀ	
궤			-	E	-				=	=	_	1-	-	-	1	il.	h	ł	li	il	!	ŀ										:
	il	lii	Ē	-		-	$\dagger$	İ.	-	-		- -	-		-		H	ii	f	H		-	-   -		41	╡				H		┼
H			E	E	-	F	-		_	_	-  -	- -	-	-	╬	¦.		H	H	1		F			4	1						
		Щ! Гі і	Ξ	-	-		-			_	1	-			1	4		11	μ.	11		-		44	11	1	<u>il:</u>	-		1.1.	Ļ	1:
			Ē		-1-	1-1					-		Ŀ				[]	H				-	1		ij		11	1	1	1	11	
			E	F	-	-			Ξ	Ξ		E	-	-		•	IT	Ü	ll			E	· ]	1	11	]			_1.			1
1.1.1			Ē		-+-	-		+				+	-		·   ·		4	$\frac{11}{11}$	ŀ	Ц	-		+	H	11	4	11;	-	+-	ŀŀ	Ŀ	ļ.
扭			-	-	Ŧ				-	╞		╞	-		-		i l			ļ	-	_	- -	H								
		$\left\  \right\ $	E		1			4	-	-	+		H	+	H	-			<u>  </u>	Щ	-		4	ļ		4			╧	- <u> </u> -	·	
-1-			-	-	- -				╉	-	_		-	- -	-						-			11					_[_		1.	Ì
				_	1	1		1			1	1	[_]	1				tl		li	Ľ		Ϊİ	li	jĮ				- -		ŀŀ	
<u>111</u> rith	1	#		_	_	H		+-		_				_	H	+			Ц		+	Ľ	1	μ	<u>  </u>	-			1	1	Ľ	1
		ĥ	-	-	+	-		+		_	+-	+-		-		-	<u>.</u>		H		-		-1-1	╬	$\frac{1}{11}$	+		╀	• • •		- <u>-</u>	H
	11	Ħ	-	_	-	1	Ţ	+	_ -		- -	1	1	+		H	t				-		1	┟	H			ł	+-	-		$\vdash$
<u>i</u> ii	'n	Ħ	-		İ	Ħ	T	†	1	_	Ì	÷		÷.		ť		il			-		+	H	<u>  </u> 			+				
		$\frac{\Pi}{\Gamma}$		-	1	1	+		-					+		+	1		11		-		11	H	<u>  </u>	4		1	-   -	1	1	Ľ
<u>11.</u> ].		2			1			-	1			Ŀ		-  -	17		i		i		1		11		1				.:	•	-	
	H			-	÷	11		-				E	-		-   -		ľ				-		늺		H					1	• • •	
NI		Ţ		-	<u>-</u>  -	ł	T	1-	- -		-[-	121	5	-1-	1-1	17	j	T	İ	Ti	1	-1	11	h	11			t		-	;	H
	KI	ij.		-	- -	ļ.		-		_ -	t	Ŀ	-	÷	Ľ						+	-			H							
(	5	1		-) -	-+-						-1-	1.		 ::::::	1.1	Ť	لىك 11					1	1		11	T	11	ŀ			+	
	$\left  \right\rangle$	X	P	7	-!					-  -	1.			<u>+-</u> -[				T	-	<u>+</u>		1				-					<u>.</u>	÷
	4	<u> </u>	L	) O	7	ľ		-	-!-		1-	-				Ļ		ļ	1	1	-	_	11						11:	•	!	
			-	-			K	1			-	-			-	ļ	H	İ		ļ	-	-	11			l	ų;	ļ.	- -			
			-	•		<u>``</u>		X	-		1-	-	-			ļļ	1	ļ	lj	li	L	4		l		Ľ	<u> ;</u> ]	Ľ			-	
	lii		-					ĸ	$\hat{\lambda}$	X	-	<u> -</u>	-				il	1	;;	įł,	-					ľ	H:	L	$\left  \cdot \right $	1		i
		H	j				ľ	-	<u>6</u>	$\sim$	N		-	+	-			ł		H	-	-					11)  1			1	ł	
111	<u>!!</u>	1.	1	-	T	Í	1.	F	11	Ŷ	Ŋ	2	5	11	ľ	1	<u>il</u>	i	11	ļl	1	ľ	11	i	ij!	1	ii.				i	
	╎╵	H		+		; 	<del> '</del>	1-			1 ( 		ä	H	+	$\left  \cdot \right $	÷	'n	<u></u>	5	$\lambda$	ં	0	Ŀ		ŀ		-	÷			i
	l'		-1		+	1.	t;	†_	÷	÷	-	-		$\left  \right\rangle$	1	ł;	5	ł	$\frac{1}{2}$	Ľ	-	+	<u>.</u>		2-	p	Q	Þ.	5	+	-	-
+++	<u>† 7</u>			t	<u> </u>	1	÷	┢	1	+			+	$\frac{1}{1}$	$\frac{1}{1}$		$\frac{\odot}{1}$	+	1	11		+		+		÷	i) 1	┢	+		$\frac{1}{1}$	4
111		1 •	+	╉	<u> </u>	1	<u> '</u> -	+-	Ļ	1	1		-	11	-  ·	ļĹ	<u>i  </u>	4	4	11	μ	1	1	1	11	1	ú	-	<u>[1</u> ]	<u>i</u>	i	4
1						1		-	1-		12				-	Ľ	: :	i	ġ	-		.;	. :			_	· .			-		
뷥			-		-	-		=			-	-			-			1							ł.	ь 1		-		:		
11			-		i i	1		-	1-		17	-	į-	ļ.	-	T	Ī	Ì	1	İİ		:1:	i i		;			F				
			-1	-	Ŀ	· i	ļ	=	·		-	-	1		Ì				į!	ji E					Ц	ľ						
	i.	Ì	7		i.		•	=	-	i:	.  .	-		1 1 1.4	1	i		i	•		•	1				Γ				[		
1					1	1	i		1	-	1-	-	1		-1		ij	Ī	H			Ţ					• • • •	-	Ţ			-
i h				+	÷	<u></u> 11		1-	i		<u></u>	•		+ +   +	<u></u>	╟		$\frac{1}{1}$	11	-1		:	<u>-</u>		1+ +	Ľ		-	-	-		÷
			-	-		1		E	1	E	E	-	- -		-	ŀ		il			ļ				i: E				.	:		
		+		+	Ħ	÷	H		1-	1_		-	1	H	<u> </u>	ļ÷		╢			$\frac{1}{1}$	+		+	$\frac{1}{1}$	ŀ-	_	-	$\frac{1}{1}$		<u>.</u>	-
	i		-	ŀ	-	Ì		-	-	Ŀ	E	-	t	łł	ł							1			ĥ	ł				!	1	
				-	$\left  \cdot \right $				- -	+	$\left  - \right $	- -	ł	$\left\  \cdot \right\ $								ľ			ļ	Ľ.				!	1	1
<b>.</b>			- ł _	-	<u>لية</u> 1	/		~	Ń				4	لمعنة	4	<u> </u>	<u> </u>	_ <u>_</u> _		-1	-	<u>'</u>	بب	<u></u>	<u> </u>	÷	لت	L.,	<u>.</u>			
						(	J	L	J	U	1																					

# APPENDIX

3



TABLE 2 DATA - S	2 STRAIGHT	TUBE

### Tubing

Length Between Pressure Taps Average Fluid Temperature 0.093" O.D. x 0.078" I.D. (nominal) 0.081" I.D. (actual) 123.8" 74°F

 $\gtrsim$ 

а. А	Notebook *		Inlet			Reynolds	Fanning Friction	Adjusted Reynolds Number	Corrected Fanning Friction Factor
Point Number	Page No. & Section	Fluid Used	Pressure (PSIA)	Drop	$\frac{(1/\min.)}{}$	_(NRe)	(f)	(N <sub>Re</sub> )	(f)
	02-1	He	33.54	11.63 H <sub>2</sub> O	2.60	233	0.0604	225	0.0716
1	03-1	11	33.7	8.88	2.00	179	0.0787	173	0.0933
2	11	**	33.9	6.40	1.46	131	0.107	127	
3	**	**	34.0	4.57	1.04	93	0.152	89.9	0.105
- 41 E	**	TT	34.1	3.40	0.74	66	0.223	63.8	0.129
Ð	**	**	33.9	5.59	1.31	117	0.116	113	0.130
	11	TT .	33.8	7.77	1.78	159	0.0870	154	0.0010
	11	**	33.7	10.45	2.31	207	0.0691	200	0.0607
0	**	**	33.5	13.13	3.01	269	0.0512	260	
9	11	11	33.7	1.76 Hg	5.50	493	0.0276	476	0.0321
11	**	11	33.1	3,65	10.75	964	0.0146	932	0.0173
12	**	**	32.8	4.57	13.80	1238	0.0109	1197	
10	**	tt ·	32.2	6.58	18.30	1641	0.00863	1586	0.0102
16	**	**	32.7	5.68	16.25	1457	0.00964	1408	0.0114
16	**	**	33.5	4.04	11.95	1072	0.0132	1036	0.0130
10	11	**	34.0	~ 2.58	7.85	704	0.0200	680	0.0469
10	**	**	34.5	1.20	3.85	345	0.0396	333	0.0405
10	11	No	69.5	11.4	14.75	10500	0.00739	10140	0.00810
24	**	11	67.5	21.67	20.7	14700	0.00667	14208	0.00751
40	**	**	64.5	40.52	27.15	19300	0.00635	18653	0.0075
20		* *	118.1	31.98	36.54	26000	0.00669	25129	0.00013
20	11	**	116.2	41.20	41.30	29400	0.00553	28415	0.00896
23	**	**	91.4	6.92	13.3	9450	0.00756	9133	0.00828
. JI . 29	TT	**	90.0	11.74	17.7	12600	0.00698	12170	0 00765
. 22	11	**	88.2	20.52	23.8	16900	0.00645	10334	0.00710
24	**	**	85.8	31.87	29.7	21100	0.00599	20400	0.00967
25	11	**	61.0	46.95	7.47	5222	0.00816	5047 490 <b>9</b>	0.0101
30		**	61.3	34.80	6.37	4441	0.00848	4292	-0.0101
30	11	11	61.5	25.33	5.35	3716	0.00886	3592	0.0109
31 20	**	**	61.7	16.85	4.32	2984	0.00921	2884	0.0105
20	.? ?	**	62.1	7.25	3.32	2224	0.00718	4149 1 400	0 0120
3 <del>3</del> 40	**	**	62.0	4.82	2.35	1528	0.0101	1411	0 0110
40	**	**	61.7	12.74	3.81	2594	0.00924	2007	0 0104
44	, 11	**	61.5	20.51	4.84	3361	0.00877	3240 EDE1	0.00956
40	11	11	77.8	48.52	8.65	6054	0.00806	5851	0.00967
44 45	**	* *	78.1	41.75	8.03	5600	0.00816	5412	0.00001

\*Air Products Research Notebook No. 142

- 35 -

		•			TABLE 3 DATA - COIL	0.048			·
			Tubing Average Flu Mandrel O.D. Finned Length Betw Diameter Tu Number of	id Temperature i Tube een Pressure I ıbe/Diameter C <b>C</b> oils	'aps oil	0.093'' 0.081'' 73°F 1.543'' 0.181'' 325.5'' .0478'' <b>59</b>	O.D. x 0.078" I. I.D. (actual)	D. (nominal)	
Point <u>Number</u>	Notebook * Page No. & Section	Fluid Used	Inlet Pressure (PSIA)	Pressure Drop	Flow	Reynolds Number <u>(NRe)</u>	Fanning Friction Factor (f)	<u>    fs     </u> <u>    fc     </u>	$(D/D_c) \stackrel{13}{e} f_s / f_c$
2 3 4 5	79-1 ''	N2 ''	91.7 90.7 90.4 89.1	6.34 HG 11.98 19.52 32.85	.205 SCFM .316 .417 .540	3972 6118 8080 10438	0.0164 0.0126 0.0116 0.0109 0.0112		
6 7 8 12	11 11 11 11	11 11 11	89.5 87.2 87.0 199.0	15.5 PSI 32.2 39.1 29.1	.526 .731 .784 1.17	10148 14111 15174 22400 28705	0.0104 0.0104 0.0966 0.0907	- - -	- - -
13 14	TT TT	T T T T	195.9 193.0	48.2 76.8	1.49	35278	0.0867	-	- · -

2 6	70-1	No	91.7	6.34 HG	. 205 SCFM	3912	0.0101		_
· 4	19-1	1,2	90 7	11.98	.316	6118	0.0126	-	_
3		**	Q0 4	19 52	. 417	8080	0.0116	-	-
4			90.1 90.1	32 85	540	10438	0.0109	-	-
5		••	90 5	15 5 PSI	. 526	10148	0.0112	-	
6	11		07.0	20.0 101	731	14111	0.0104	-	-
7	**		01.4	20.1	784	15174	0.0104	-	-
8			87.0	20.1	1 17	22400	0.0966	-	-
12	77	**	199.0	40.0	1 /0	28705	0.0907	-	-
13	* **	11	195.9	48.4	1.43	35278	0.0867	-	-
14	**	**	193.0	76.8	1.03	22151	0 0874	-	·
15	**	**	376.0	30.0	1.74	JJ1J1 11556	0.0822	-	-
16	**	TT	371.1	53.3	2.34	44000	0.0801	_	-
17		11	370.5	52.2	2.34	44000	0.0760	_	-
18	1, 11	**	367.5	72.1	2.75	50900	0.0769	-	-
19	11	**	365.2	91.2	3.06	58280	0.0735	-	-
20	**	**	398.5	95.7	3.32	63209	0.0135	707	1.362
1	80-1	He	37.2	4.57 HG	4.1 $1/\min$ .	357	0.0034	697	1.353
2	11	**	36.9	8.59	6.4	556	0.0414	544	1.160
3	**	**	36.6	13.9	8.8	764	0.0304	491	1, 101
4	**	**	36.3	20.8	11.2	973	0.0334	. 401	1, 136
5	. **	17	36.6	16.7	10.0	870	0.0350	. 525	1.209
J C	**	**	37.0	10.8	7.6	660	0.0414	. 303	1 287
0	11	**	37.5	6.38	5.2	451	0.0547	. 041	1 570
1 1	80-2	**	44.4	7.4 H <sub>2</sub> O	0.74	64.3	0.293	.040	1 478
11	00-2	**	44.4	18.7	1.67	145	0.140	. 100	1 320
14	**	**	44.1	36.5	2.90	252	0.0944	.014	1 523
13	11	11	44.4	12.7	7.22	106	0.185	.810	1 326
15	11		43.9	44.7	3.45	300	0.0788	.010	1 416
16			43.9	33.4	2.85	247	0.0871	. 743	1.519
17		**	44 1	21.8	2.05	178	0.111	. 809	1.014
18		**	63 4	5.34	8.8	209	0.106	. 722	1,000
25	••	11	63 2	10.3	13.6	153	0.132	. 792	1.400
26		11	62.8	14.0	16.6	98.6	0.191	. 849	1,010
27	••	••	62.5	18.2	19.5	65.7	0.279	. 873	1.012
28	**	••	02.0	10.2					<b>.</b>

·

\* Air Products Research Notebook No. 142

2 - +

- 36-

	:					ана (1997) 1997 — Салан Салан (1997) 1997 — Салан (1997)
• .						
· .						
×	:					
					:	
	· . ·					
			5 1.			<b>)</b> .
						•
		• •	_			

TABLE 4 DATA - COIL 0.100

Tubing

Average Fluid Temperature Mandrel O.D. Finned Tube Length Between Pressure Taps Number of Coils 0.093" O.D. x 0.078" I.D. (nominal) 0.081" I.D. (actual) 73°F 0.625" 0.181" 194.0" 79 Ć

÷.,

$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Point Number	Notebook * Page No. & Section	Fluid Used	Inlet Pressure (PSIA)	Pressure Drop	Flow	Reynolds Number (N <sub>Re</sub> )	Fanning Friction Factor (f)	fs fc	(D/D <sub>c</sub> ) 13 (D/D <sub>c</sub> ) f <sub>s</sub> /f <sub>c</sub> e
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$		79-1	No	116.7	1.78 Hg	3.17 l/min	2630	0.0251	-	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	1.	10-1		116.0	6.61	9.15	6490	0.0151	-	_
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	2	**	"	115.5	10.63	12.0	8500	0.0139	-	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	3	17	**	114.5	18.36	16.5	11700	0.0123	-	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	*1 5	**	**	113.5	28.56	<b>∠21.</b> 05	14900	0.0115	-	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	J C	**	17	112.9	36.05	23.5	16700	0.0113	-	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	U .	*1	**	65.5	7.78	6.97	4940	0.0170	-	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	10	11	**	63.5	24.80	13.48	9560	0.0132	-	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	10	**	**	62.7	35.95	16.07	11400	0.0127	-	_
121111111236.733.0225000.010615"""114.525.00.99 SCFM191000.010116""""114.525.00.99 SCFM191000.010116""""109.062.21.41273000.010017""""109.062.21.41273000.010020"""210.015.733.5215000.010621"""208.222.01.61311000.0096422"""203.843.21.66360000.0093123"""203.843.21.66360000.0086824"""203.664.02.85544000.008682578-4""30.792.13.98751000.0081129""""286.792.13.98751000.008113078-5He33.823.012.971/min2550.10131""<">"33.910.121.121000.0218.7341.63232"""33.910.121.121000.218	11	78-2		118.3	12.2 PSIA	19.7	13400	0.0117	-	
15       "       "       114.5       25.0       0.99 SCFM       19100       0.0108       -       -         16       "       "       112.0       38.3       1.19       23000       0.0101       -       -         19       78-3       "       211.5       9.3       23.8       1.11       27300       0.0106       -       -         20       "       "       210.0       15.7       33.5       218.00       0.0106       -       -         21       "       "       206.2       32.0       1.64       31000       0.00964       -       -         23       "       "       200.0       65.4       2.24       48100       0.00868       -       -         24       "       "       300.4       49.2       2.52       48100       0.00868       -       -         25       78-4       "       300.0       75.2       146       60300       0.00829       -       -         29       "       "       33.7       33.7       HgO       2.97 1/min       2868       0.101       -       -         21       "       33.9       6.59       0.	14	10 2	**	112.5	36.7	33.0	22500	0.0106	-	
13""112.038.31.19230000.010117""109.062.21.41273000.01001976-3"211.59.323.81/min162000.011120""200.015.733.5215000.010621""209.219.01.24 SCFM240000.010121""206.232.01.6631000.0093422"""200.065.42.24431000.0093424""200.065.42.24481000.008382578-4"300.449.22.552481000.008392578-5He33.7H2O2.971/min28580.10129"""33.823.02.151870.13364331.63231""33.910.121.121000.218.7341.54233""33.910.121.121000.218.7341.54234""33.910.121.121000.218.7341.54235""55.920.701.73150 </td <td>14</td> <td>**</td> <td>,,</td> <td>114.5</td> <td>25.0</td> <td>0.99 SCFM</td> <td>19100</td> <td>0.0108</td> <td>-</td> <td>_</td>	14	**	,,	114.5	25.0	0.99 SCFM	19100	0.0108	-	_
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	10	**		112.0	38.3	1.19	23000	0.0101	-	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	10	"	**	109.0	62.2	1.41	27300	0.0100	-	-
$13^{\circ}$ $11^{\circ}$ $1210.0$ $15.7$ $33.5$ $21500$ $0.0106$ $  21$ $11^{\circ}$ $209.2$ $19.0$ $1.245 \text{CFM}$ $24000$ $0.0101$ $  21$ $11^{\circ}$ $206.2$ $32.0$ $1.61$ $31100$ $0.00964$ $  22$ $11^{\circ}$ $11^{\circ}$ $200.6$ $65.4$ $2.24$ $43100$ $0.00934$ $  24$ $11^{\circ}$ $1200.0$ $65.4$ $2.24$ $43100$ $0.00868$ $  25$ $78-4$ $11^{\circ}$ $300.4$ $49.2$ $2.52$ $48100$ $0.00868$ $  26$ $11^{\circ}$ $11^{\circ}$ $294.9$ $64.0$ $2.85$ $54400$ $0.00858$ $  27$ $11^{\circ}$ $11^{\circ}$ $296.7$ $92.1$ $3.98$ $75100$ $0.00811$ $  29$ $11^{\circ}$ $13.8$ $23.0^{\circ}$ $2.971$ $17m$ $2153$ $0.103$ $643$ $1.408$ $31$ $11^{\circ}$ $13.8$ $23.0^{\circ}$ $2.971$ $17m$ $2153$ $0.103$ $643$ $1.622$ $33$ $11^{\circ}$ $33.8$ $12.39^{\circ}$ $17.83$ $1.79$ $155$ $0.149$ $693$ $1.623$ $33$ $11^{\circ}$ $13.39$ $17.83$ $1.79$ $155$ $0.149$ $693$ $1.624$ $34$ $11^{\circ}$ $11.97$ $1.10$ $96$ $0.221$ $1754$ $1.573$ $35$ $11^{\circ}$ $11.97$ <	10	78-3	11	211.5	9.3	23.8 l/min	16200	0.0111	-	_
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	20	10 0	ii.	210.0	15.7	33.5	21500	0.0106	-	_
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	20	"	••	209.2	19.0	1.24 SCFM	24000	0.0101	-	<b>-</b> .
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	22	**	••	206.2	32.0	1.61	31100	0.00964	-	-
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	22	**	ri -	203.8	43.2	1.86	36000	0.00934	÷ [	-
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	23	**	**	200.0	65.4	2.24	43100	0.00901		-
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	25	78-4	17	300.4	49.2	2.52	48100	0.00888	-	=
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	25		**	294.9	64.0	2.85	54400	0.00858		-
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	20	**	**	309.0	75.2	3.16	60300	0.00839	-	-
$30$ $78-5$ He $33.7$ $33.7$ $H_2O$ $2.97$ $1/\min$ $2858$ $0.101$ $0.101$ $31$ "" $33.8$ $23.0$ $2.15$ $187$ $0.133$ $643$ $1.408$ $31$ "" $33.9$ $6.59$ $0.76$ $66$ $0.309$ $790$ $1.632$ $32$ "" $33.9$ $10.12$ $1.12$ $100$ $0.218$ $734$ $1.542$ $33$ """ $33.9$ $10.12$ $1.12$ $100$ $0.218$ $734$ $1.542$ $34$ """ $33.9$ $17.83$ $1.79$ $155$ $0.149$ $693$ $1.482$ $34$ """ $56.7$ $11.97$ $1.10$ $96$ $0.221$ $754$ $1.573$ $36$ """ $56.7$ $11.97$ $1.10$ $96$ $0.221$ $754$ $1.573$ $37$ "" $56.7$ $11.97$ $1.10$ $96$ $0.221$ $754$ $1.573$ $37$ "" $56.3$ $16.20$ $1.42$ $124$ $0.179$ $721$ $1.525$ $37$ "" $36.5$ $6.08$ $6.40$ $556$ $0.0560$ $513$ $1.237$ $28$ $79-3$ " $36.5$ $6.08$ $6.40$ $556$ $0.0660$ $513$ $1.237$ $29$ """ $36.5$ $14.5$ $11.20$ $973$ $0.0405$ $425$ $1.113$ $30$ """	29	"	**	286.7	92.1	3.98	75100	0.00811	_	-
31"33.823.02.15 $187$ $0.133$ $103$ $1632$ 32""33.9 $6.59$ $0.76$ $66$ $0.309$ $790$ $1.632$ 33"""33.9 $10.12$ $1.12$ $100$ $0.218$ $734$ $1.542$ 33""" $33.9$ $17.83$ $1.79$ $155$ $0.149$ $693$ $1.482$ 34""" $33.9$ $17.83$ $1.79$ $155$ $0.149$ $693$ $1.624$ 35""" $57.1$ $8.49$ $0.82$ $72$ $0.283$ $785$ $1.624$ 36""" $56.7$ $11.97$ $1.10$ $96$ $0.221$ $754$ $1.573$ 36""" $56.3$ $16.20$ $1.42$ $124$ $0.179$ $721$ $1.495$ 38""" $55.9$ $20.70$ $1.73$ $150$ $0.152$ $701$ $1.495$ 38""" $36.8$ $3.3$ Hg $4.10$ $357$ $0.0762$ $588$ $1.334$ 28 $79-3$ " $36.6$ $6.40$ $556$ $0.0560$ $513$ $1.166$ 30""" $36.3$ $9.8$ $8.80$ $764$ $0.0461$ $453$ $1.111$ $31$ """ $36.5$ $7.63$ $7.60$ $660$ $0.0490$ $494$ $1.214$ $33$ """ $63.2$ <td< td=""><td>30</td><td>78-5</td><td>He</td><td>33.7</td><td>33.7 Н<sub>2</sub>О</td><td>2.97 l/mii</td><td>n 2858</td><td>0,101</td><td>643</td><td>1, 408</td></td<>	30	78-5	He	33.7	33.7 Н <sub>2</sub> О	2.97 l/mii	n 2858	0,101	643	1, 408
32" $33.9$ $6.59$ $0.76$ $66$ $66$ $0.308$ $1.50$ $1.542$ $33$ "" $33.9$ $10.12$ $1.12$ $100$ $0.218$ $.734$ $1.542$ $34$ "" $33.9$ $17.83$ $1.79$ $155$ $0.149$ $.693$ $1.482$ $34$ "" $33.9$ $17.83$ $1.79$ $155$ $0.149$ $.693$ $1.624$ $35$ "" $57.1$ $8.49$ $0.82$ $72$ $0.283$ $.785$ $1.624$ $36$ "" $56.7$ $11.97$ $1.10$ $96$ $0.2211$ $.754$ $1.525$ $37$ "" $56.3$ $16.20$ $1.42$ $124$ $0.179$ $.721$ $1.525$ $37$ "" $56.3$ $16.20$ $1.42$ $124$ $0.179$ $.721$ $1.525$ $37$ "" $56.3$ $16.20$ $1.42$ $124$ $0.179$ $.721$ $1.525$ $37$ "" $36.8$ $3.3$ Hg $4.10$ $357$ $0.0762$ $.588$ $1.334$ $28$ $79-3$ " $36.5$ $6.08$ $6.40$ $556$ $0.0560$ $513$ $1.237$ $30$ "" $36.5$ $7.63$ $7.60$ $0.0422$ $.434$ $1.143$ $32$ """ $36.5$ $7.63$ $7.60$ $660$ $0.0490$ $.494$ $1.214$ $33$ """ $36.5$ $7.63$ $7.60$ <td>31</td> <td></td> <td></td> <td>33.8</td> <td>23.0</td> <td>2.15</td> <td>187</td> <td>0.133</td> <td>700</td> <td>1,632</td>	31			33.8	23.0	2.15	187	0.133	700	1,632
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	32	rt'	**	33.9	6.59	0.76	66	0.309	734	1,542
34"" $33.9$ $17.83$ $1.79$ $155$ $0.149$ $1657$ $35$ "" $57.1$ $8.49$ $0.82$ $72$ $0.283$ $.785$ $1.624$ $35$ "" $57.1$ $8.49$ $0.82$ $72$ $0.283$ $.785$ $1.573$ $36$ "" $56.7$ $11.97$ $1.10$ $96$ $0.221$ $.754$ $1.573$ $37$ "" $56.3$ $16.20$ $1.42$ $124$ $0.179$ $.721$ $1.525$ $37$ "" $55.9$ $20.70$ $1.73$ $150$ $0.152$ $.701$ $1.495$ $38$ """ $55.9$ $20.70$ $1.73$ $150$ $0.152$ $.588$ $1.334$ $28$ $79-3$ " $36.6$ $3.3$ $Hg$ $4.10$ $357$ $0.0762$ $588$ $1.237$ $29$ """ $36.5$ $6.08$ $6.40$ $556$ $0.0560$ $513$ $1.237$ $29$ """ $36.5$ $9.8$ $8.80$ $764$ $0.0461$ $453$ $1.166$ $31$ "" $36.5$ $9.8$ $8.80$ $764$ $0.0461$ $453$ $1.111$ $31$ """ $36.5$ $7.63$ $7.60$ $660$ $0.0422$ $434$ $1.143$ $33$ """ $36.9$ $4.51$ $5.20$ $451$ $0.0642$ $551$ $1.286$ $34$ """ $36.9$	33		**	33.9	10.12	1.12	100	0.218	693	1.482
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	34	11	**	33.9	17.83	1.79	100	0.145	. 785	1.624
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	35	**		57.1	8.49	0.82	12	0.200	. 754	1.573
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	36	**		56.7	11.97	1.10	190	0.179	. 721	1.525
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	37	**	••	56.3	16.20	1.42	124	0.152	. 701	1.495
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	38	**	**	55.9	20.70	1. 13	150	0.0762	588	1.334
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	28	79-3	**	36.8	3.3 Hg	4, 10	301	0.0102	513	1,237
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	29	**	**	36.5	6.08	6.40	555	0.0300	453	1.166
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	30	**		36.3	9.8	8.80	764	0.0401	425	1.111
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	31	"	••	35.9	14.5	11.20	973	0.0403	434	1.143
33       "       "       36.5       7.63       7.60       660       0.0432       1.21       1.286         34       "       "       36.9       4.51       5.20       451       0.0642       .551       1.286         34       "       "       36.9       4.51       5.20       451       0.0642       .551       1.286         26       "       "       63.2       10.26       H2O       13.6       1/min       1180       0.0383       .353       1.053         26       "       "       62.8       14.04       16.6       1440       0.0384       .324       1.024         27       "       "       62.5       18.2       19.5       1690       0.0313       .302       1.002	32	**	**	36.1	11.77	10.00	870	0.0422	494	1,214
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	33	••	**	36.5	7.63	7.60	451	0.0430	. 551	1.286
26       "       "       63.2       10.26 H2O       13.6       1/min       1180       0.0300       .324       1.024         27       "       "       62.8       14.04       16.6       1440       0.0384       .324       1.024         28       "       "       62.5       18.2       19.5       1690       0.0313       .302       1.002	34	"	**	36.9	4.51	5.20 19 6 1/	- 1190	0.0383	353	1.053
27       ''       ''       62.8       14.04       10.6       1440       0.0011       302       1.002         28       ''       ''       62.5       18.2       19.5       1690       0.0313       .302       1.002	26	*1		63.2	10.26 H <sub>2</sub> O	13.0 1/ml	1440	0.0384	. 324	1.024
	27	**		62.8	14.04	10.0	1690	0.0313	. 302	1.002
	28	**	••	62.5	10.2	19.0	1000			

\*Air Products Research Notebook No. 142

.

. ł. .

. .

- 37 -

# DATA - COIL 0. 125

### Tubing

Average Fluid Temperature Mandrel O.D. Finned Tube Length Between Pressure Taps Number of Coils 0.093" O.D. x 0.078" I.D. (nominal) 0.081" I.D. (actual) 72°F 0.467" 0.181" 123.0" 59

-

Point Number	Notebook * Page No. & Section	Fluid Used	Inlet Pressure (PSIA)	Pressure Drop	Flow (l/min)	Reynolds Number (NRe)	Fanning Friction Factor (f)	f <sub>s</sub> f <sub>c</sub>	$(D/D_c)$ $\begin{array}{c} .13 \\ f_s/f_c \\ e \end{array}$
· ·	09 1	No	89 5	1.97 Hg	4.20	2910	0.0255	-	-
2.	02-1	12	80.1	3 90	6.77	4690	0.0192	-	-
. 3			00.1	5 04	7 90	5460	0.0181	-	
4	**		09.0	6 10	9 00	6220	0.0171	-	-
5	**		88.7	0.13	11 00	8160	0.0161	-	<b>-</b> , · · ·
6	**	11	88.1	10.23	11.00	10500	0 0148	-	-
7	**	11	87.4	16.16	15.30	10000	0.0141	_	- ·
8	11	17	86.6	21.23	17.70	12250	0.0141		_
· 0		**	85.8	28.66	20.70	14300	0.0134	-	_
5	11	**	85.0	36.35	23.0	15900	0.0133	-	. –
10	••	11	109 0	17.90 PSI	26.8	18450	0.0130	-	-
11	••		107 3	22 7	29.9	20600	0.0128	-	-
12			101.5	28.4	33.0	22700	0.0124	-	-
13	f f		100.0	20.1	28 1	19350	0.0129	-	

13			100.5	20.0	28 1 ·	19350	0.0129	-	-
14	TT		106.5	20.0	19 4	29200	0.0118	-	-
16	11	**	98.8	00.0	40 2	33700	0.0113	-	-
17	**		165.7	35.4	49.0	20150	0 0111	-	-
18	**	**	<b>162.</b> 5	48.2	56.2	20400	0.0110	<u> </u>	-
19	**	11	158.7	66.2	63.3	43300	0.0105	_	-
21	**	**	157.3	63.9	63.5	43300	0.0105	-	-
22		11	305.0	40.0	76.8	51600	0.0101	_	· _
23	**	**	300.5	56.8	90.1	60600	0.0101	_	_
24	11	**	295.2	78.0	103.5	69600	0.00963	579	1,350
25	11	He	33.7	18.52 Н <sub>2</sub> О	2.42	210	0.133	- 51Z - 602	1, 393
26	**	11	33.7	14.45	1.98	171	0.155	. 003	1 410
20	**	11	33.8	10.28	1.47	128	0.203	. 010	1 449
21	**	**	33.8	6.96	1.02	88	0.285	. 638	1 449
20		**	33.8	8.28	1.22	105	0.237	. 643	1 404
29	**	**	33 9	5,02	0.77	66.6	0.360	. 667	1.404
30	**	**	33 8	12.39	1.75	152	0.172	. 612	1.404
31		**	33 6	16.90	2.25	194	0.141	. 584	1.300
32		**	33 6	21.40	2.82	244	0.113	. 580	1.300
33		**	22.5	31.25	3.90	337	0.0855	. 554	1.326
34		11	33 4	45 45	4,95	428	0.0765	. 488	1.241
35			22.1	7 05 Hg	8.35	722	0.0557	. 397	1.138
36	•••		00.9 99 9	12 32	11.95	1034	0.0488	. 3155	1.044
37	11		22.2	19 16	15.70	1350	0.0382	. 309	1.028
38			00.9 00 0	25 68	18 60	1600	0.0346	. 289	1.017
39	11	11	33.8	14.70	13.66	1180	0.0409	. 330	1.060
41			34 3	9.32	10.1	870	0.0492	. 367	1,100
42	11		24.0	4 90	6.6	570	0.0645	. 434	1.175
43	**		34.0	1.00					

\* Air Products Research Notebook No. 142

...

- 38-

TABL	E 6			
<u>LAPIN</u>	DATA	-	COIL	0.030
		_		

Tubing Mean Coil Diameter Length Between Pressure Taps Diameter Tube/Diameter Coil Number of Coils 0.0413 Ft. 1.395 Ft. 19.72 Ft. 0.0295" 4.5

Point Number	Notebook * Page No. & Section	Fluid Used	Outlet Pressure (Hg)	Pressure Drop	Average Temperature °C	Flow (SCFM)	Reynolds Number (N <sub>Re</sub> )	Fanning Friction Factor Before Coiling (Straight)
1.	25-1	Air	2.45	3.30" Hg	19.0	11.21	32, 480	. 00562
$\overline{2}$	<b>t</b> 1	**	2.30	3.10"	19.0	10.87	31, 470	. 00558
3	**	**	2.30	3.10"	19.0	10.64	30, 800	. 00583
4	**	**	2.05	2.70"	19.0	9.71	28, 110	. 00601
5	**	**	160	2.05"	19.0	8.44	24, 440	. 00591
6	**	**	1.00	9.40" H <sub>2</sub> O	18.0	4, 59	14, 450	. 00690
7	TT	**	0.95	8.10"	20.0	4.16	13, 100	. 00720
8	**	**	0.75	6.80"	19.5	3.75	11, 810	. 00732
9.	TT	**	0.75	5. 60"	19.2	3.34	16, 510	. 00765
10	**	**	0.65	4. 70''	19.0	3.01	9,480	. 00787
							-,	

12       "       "       0.60       3.40"       18.5       2.46       7,740       .00848         13       "       "       0.50       2.95"       18.0       2.28       7,180       .00855         14       "       "       0.45       1.50"       18.5       1.58       4,970       .00898         4         27,28-1       Air       1.3       7.8" H2O       22.5       3.83       12,050       .00763         5       "       1.15       8.4"       22.5       3.28       10,330       .00768         6       "       "       1.5       8.4"       22.5       4.57       14,390       .00757         7       "       "       0.6       1.3"       22.5       1.43       4,500       .00961         9       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       24.0       5.17       14,980       .00768         12       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.	11	**	**	0.70	4. 20''	19.0	2.80	8,810	. 00813
13       "       "       0.50       2.95"       18.0       2.28       7,180       .00855         14       "       "       0.45       1.50"       18.5       1.58       4,970       .00898         After Colling         4       27,28-1       Air       1.3       7.8"       H <sub>2</sub> O       22.5       3.83       12,050       .00763         5       "       "       1.0       -5.3"       22.5       3.28       10,330       .00768         6       "       "       1.5       8.4"       22.5       4.20       13,220       .00757         7       "       "       0.6       1.3"       22.5       1.43       4,500       .00961         9       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00761         11       "       "       2.2       1.43       4,500       .00728         12       "       "       1.8       10.2"       24.0       5.52       15,990       .00724         11       "	12	**	**	0.60	3. 40"	18.5	2.46	7,740	. 00848
14       "       0.45       1.50"       18.5       1.58       4,970       .00898         4       27,28-1       Air       1.3       7.8"       H2O       22.5       3.83       12,050       .00763         5       "       1.0       -5.3"       22.5       3.28       10,330       .00763         6       "       "       1.6       8.4"       22.5       3.28       10,330       .007677         7       "       "       2.6       9.8"       22.5       4.57       14,390       .00774         8       "       "       0.6       1.3"       22.5       0.97       3,050       .00760         9       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00728         13       "       "       2.6       16.1"       24.0       5.52       15,990       .00681         14       "       "       2.9       19.3"	13	**	**	0.50	2.95"	18.0	2.28	7, 180	. 00855
i         i	14	**	**	0.45	1.50"	18.5	1.58	4, 970	. 00898
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $						<b>*</b>			
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$					с. <sup>2</sup>	ť			After Coiling
5       "       "       1.0       5.3"       22.5       3.28       10,330       .00768         6       "       "       1.5       8.4"       22.5       4.20       13,220       .00757         7       "       "       2.6       9.8"       22.5       4.57       14,390       .00774         8       "       "       0.6       1.3"       22.5       1.43       4,500       .00961         9       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00728         12       "       "       2.2       13.5"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19,980       .00684         15       "       "       3.7       24.2"       23.5	4	27, 28-1	Air	1.3	7.8" H <sub>2</sub> O	22.5	3.83	12,050	. 00763
6       "       "       1.5       8.4"       22.5       4.20       13,220       .00757         7       "       "       2.6       9.8"       22.5       4.57       14,390       .00774         8       "       "       0.6       1.3"       22.5       1.43       4,500       .00961         9       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00728         12       "       "       2.6       16.1"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170	5	**	**	1.0	— 5.3'' <sup>–</sup>	22.5	3.28	10, 330	. 00768
7       "       "       2.6       9.8"       22.5       4.57       14,390       .00774         8       "       "       0.6       1.3"       22.5       1.43       4,500       .00961         9       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00724         12       "       "       2.2       13.5"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       "       9.2       4.1"	6	**	. **	1.5	8.4"	22.5	4.20	13, 220	. 00757
8       "       "       0.6       1.3"       22.5       1.43       4,500       .00961         9       "       "       0.4       0.7"       22.5       0.97       3,050       .0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00728         12       "       "       2.2       13.5"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19.980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00564         30       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5	* 7		**	2.6	9.8"	22.5	4.57	14, 390	. 00774
9       "       "       0.4       0.7"       22.5       0.97       3,050       0111         10       "       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00728         12       "       "       2.6       16.1"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         30       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	8	**	**	0.6	1.3"	22.5	1.43	4, 500	. 00961
10       "       1.8       10.2"       26.0       4.65       13,460       .00760         11       "       "       2.0       12.0"       24.0       5.17       14,980       .00728         12       "       "       2.2       13.5"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	9		**	0.4	0. 7''	22.5	0.97	3,050	. 0111
11       "       2.0       12.0"       24.0       5.17       14,980       .00728         12       "       "       2.2       13.5"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170       .00728         14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	10	**	**	1.8	10.2"	26.0	4.65	13, 460	. 00760
12       "       "       2.2       13.5"       24.0       5.52       15,990       .00724         13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	11	**	**	2.0	12.0"	24.0	5.17	14, 980	. 00728
13       "       "       2.6       16.1"       24.0       5.58       16,170          14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	. 12	**	TT	2.2	13.5"	24.0	5.52	15, 990	. 00724
14       "       "       2.9       19.3"       23.7       6.90       19,980       .00681         15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	13	**	**	2.6	16. 1''	24.0	5.58	16, 170	
15       "       "       3.7       24.2"       23.5       7.82       22,650       .00684         16       "       "       4.5       28.5"       23.3       8.51       24,650       .00699         30       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	14	**	TT	2.9	19.3"	23.7	6.90	19, 980	. 00681
16""4.528.5"23.38.5124,650.0069930""9.24.1"23.013.3438,640.0056434""13.15.5"22.016.6748,280.00570	15	**	11	3.7	24. 2"	23.5	7.82	22,650	. 00684
30       "       "       9.2       4.1"       23.0       13.34       38,640       .00564         34       "       "       13.1       5.5"       22.0       16.67       48,280       .00570	16	**	**	4.5	28. 5"	23.3	8.51	24,650	. 00699
<b>34</b> " " 13.1 5.5" 22.0 16.67 48,280 .00570	30	**	11	9.2	4. 1"	23.0	13.34	38,640	.00564
	34	*1	**	13.1	5. 5''	22.0	16.67	48, 280	. 00570

\*Air Products Research Notebook No. 25

· .

.

- 39 -

¢.

• •

TABLE	7				
LAPIN	DATA	-	COIL	0.	135

Tubing	0413 ፑተ
Mean Coil Diameter	0 306 54
Length Between Pressure Taps	14 49 Et.
Diamotor Tubo /Diamotor Coil	17,74 FL. 0 175
Nameler Tube/Diameter Coll	0.155
Number of Colls	15

$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Point Number	Notebook* Page No. & Section	Fluid Used	Outlet Pressure (Hg)	Pressure Drop	Average Temperature <b>°C</b>	Flow (SCFM)	Reynolds Number (N <sub>Re</sub> )	Fanning Friction Factor Before Coiling (Straight)
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	1	25-1	Air	11.10	2.70" Hg	19.0	11 21	32 480	00573
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	2	ŤŤ	**	10.60	2.50"	19.0	10.87	31 470	.00513
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	3	11	11	10.25	2 50"	19 0	10.64	30, 800	.00537
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	4	71	**	9.00	2 25"	19.0	0.71	29 110	00602
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	5	* 7	TT	6 95	1 751	19.0	9.11	20,110	.00003
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	6	TT	**	2 65		19.0	0.44	24,440	. 00583
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	7	**	**	2.00	7 9011	10.0	4.09	14,450	. 00690
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8	**		2.00		20.0	4.16	13,100	. 00730
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	ğ	11	**	1.90	5 401	19.5	3.75	11,800	. 00740
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	10	**	**	1.10	5.40 <sup>11</sup> 4.6011	19.2	3.34	10, 510	. 00760
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	11	ŤŤ	**	1.40	4.00	19.0	3.01	9,480	. 00790
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	12	• •	**	1.40	4.10	19.0	2.80	8,810	.00810
14"1.032.90"18.02.237.180.0066014"0.701.45"18.51.584,980.00680After Coiling127,28-1Air1.13.0" H2O22.51.895.950.01802""1.54.3"22.52.367.430.01673""1.85.6"22.52.828,880.01545"2.99.2"22.53.8312,060.01435"2.37.2"22.53.2810,330.01496""3.912.2"22.54.2013,220.01397"0.81.9"22.50.973.050.022210""0.61.0"22.50.973.050.022211""4.614.7"24.05.1714.980.013812""9.026.5"23.57.8222.650.011611""4.614.7"24.05.1714.980.013214""7.222.3"23.76.9019.980.013115""9.026.5"23.57.8222.650.011616""10.529.9"23.38.5124.650.011718""10.529.9"23.38.5124.650.0117	12			1.10	3.23	18.5	2.46	7.750	. 00830
14       0.70       1.45"       18.5       1.58       4,980       .00880         After Colling         1       27,28-1       Air       1.1       3.0" H2O       22.5       1.89       5,950       .0180         2       "       "       1.5       4.3"       22.5       2.36       7,430       .0167         3       "       "       1.8       5.6"       22.5       2.82       8,880       .0167         4       "       "       2.9       9.2"       22.5       3.83       12,060       .0143         5       "       "       2.3       7,2"       22.5       3.28       10,330       .0149         6       "       "       3.9       12.2"       22.5       4.57       14,390       .0137         8       "       "       0.6       1.0"       22.5       1.43       4,500       .0138         9       "       0.66       1.0"       22.5       1.43       4,500       .0138         9       "       0.66       1.0"       22.5       0.97       3.050       .0222         10       "       4.6       1.47"       24.0       5.17 <td>14</td> <td>**</td> <td></td> <td>1.05</td> <td>2.90"</td> <td>18.0</td> <td>2.28</td> <td>7.180</td> <td>. 00860</td>	14	**		1.05	2.90"	18.0	2.28	7.180	. 00860
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	7.7			0.70	1.45"	18.5	1.58	4, 980	. 00880
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$									After Coiling
$\begin{array}{cccccccccccccccccccccccccccccccccccc$									
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	1	27, 28-1	Air	1.1	3.0'' Н <sub>2</sub> О	22.5	<b>1.89</b>	5, 950	.0180
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	2	**	11	1.5	4.3''	22.5	2.36	7,430	.0167
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	. 3	**	**	1.8	5.6"	22.5	2.82	8,880	. 0154
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	4	**	**	2.9	9.2"	22.5	3.83	12,060	. 0143
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	5	**	**	2.3	7.2"	22.5	3.28	10, 330	. 0149
7"3.912.2"22.54.5714,390.01378""0.81.9"22.51.434,500.01969""0.61.0"22.50.973,050.022210""4.012.7"26.04.6513,460.013811""4.614.7"24.05.1714,980.013212""5.116.2"24.05.5215,980.013014""7.222.3"23.76.9019,980.012115""9.026.5"23.57.8222,650.011616"""10.529.9"23.38.5124,650.011718""14.738.9"23.110.3529,980.011428""16.73.2" Hg23.011.5033,310.010830""21.23.9"23.015.1843.960.0110	6	**	**	3.4	10.6"	22.5	4, 20	13, 220	0139
8       "       "       0.8       1.9"       22.5       1.43       4,500       .0196         9       "       "       0.6       1.0"       22.5       0.97       3,050       .0222         10       "       "       4.0       12.7"       26.0       4.65       13,460       .0138         11       "       "       4.6       14.7"       24.0       5.17       14,980       .0132         12       "       "       5.1       16.2"       24.0       5.52       15,980       .0130         14       "       "       7.2       22.3"       23.7       6.90       19,980       .0121         15       "       "       9.0       26.5"       23.5       7.82       22.650       .0116         16       "       "       10.5       29.9"       23.3       8.51       24,650       .0117         18       "       "       14.7       38.9"       23.1       10.35       29,980       .0114         28       "       "       16.7       3.2" Hg       23.0       11.50       33,310       .0108         30       "       "       25.2       4.	7	* *	**	3.9	12.2''	22.5	4.57	14, 390	0137
9""0.61.0"22.50.973,050.022210""4.012.7"26.04.6513,460.013811""4.614.7"24.05.1714,980.013212""5.116.2"24.05.5215,980.013014""7.222.3"23.76.9019,980.012115"9.026.5"23.57.8222,650.011616""10.529.9"23.38.5124,650.011718""14.738.9"23.110.3529,980.011428""16.7 $3.2$ " Hg23.011.5033,310.010830""21.2 $3.9$ "23.015.1843,660.011032""25.24.4"23.015.1843,960.0101	8	**	**	0.8	1.9"	22.5	1.43	4,500	0196
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	9	**	**	0.6	1.0"	22.5	0.97	3,050	0222
11"4.614.7"24.01.0016,10010,10012""5.116.2"24.05.1714,980.013214""7.222.3"24.05.5215,980.013014""7.222.3"23.76.9019,980.012115""9.026.5"23.57.8222,650.011616""10.529.9"23.38.5124,650.011718""14.738.9"23.110.3529,980.011428""16.73.2" Hg23.011.5033,310.010830""21.23.9"23.015.1843.960.011032"""25.24.4"23.015.1843.960.0101	10	**	**	4.0	12.7"	26 0	4 65	13 460	0138
12"" $5.1$ $16.2$ " $24.0$ $5.52$ $15,980$ $.0132$ 14"" $7.2$ $22.3$ " $23.7$ $6.90$ $19,980$ $.0121$ 15"" $9.0$ $26.5$ " $23.5$ $7.82$ $22,650$ $.0116$ 16"" $10.5$ $29.9$ " $23.3$ $8.51$ $24,650$ $.0117$ 18"" $14.7$ $38.9$ " $23.1$ $10.35$ $29,980$ $.0114$ 28"" $16.7$ $3.2$ " Hg $23.0$ $11.50$ $33,310$ $.0108$ 30"" $21.2$ $3.9$ " $23.0$ $15.18$ $43.960$ $.0110$ 32"" $25.2$ $4.4$ " $23.0$ $15.18$ $43.960$ $.0101$	11	**	11	4.6	14. 7"	24 0	5 17	14 980	0130
14       "       "       7.2       22.3"       23.7       6.90       19,980       .0121         15       "       "       9.0       26.5"       23.5       7.82       22,650       .0116         16       "       "       10.5       29.9"       23.3       8.51       24,650       .0117         18       "       "       14.7       38.9"       23.1       10.35       29,980       .0114         28       "       "       16.7       3.2" Hg       23.0       11.50       33,310       .0108         30       "       "       21.2       3.9"       23.0       15.18       43.960       .0110         32       "       "       25.2       4.4"       23.0       15.18       43.960       .0101	12	**	11	5.1	· 16. 2''	24.0	5 59	15 980	.0102
15       "       "       9.0       26.5"       23.1       0.30       19,360       .0121         16       "       "       10.5       29.9"       23.3       8.51       24,650       .0116         18       "       "       14.7       38.9"       23.1       10.35       29,980       .0117         28       "       "       16.7       3.2" Hg       23.0       11.50       33,310       .0108         30       "       "       21.2       3.9"       23.0       15.18       43,960       .0101	14		**	7.2	22 3"	24.0	6 90	10,000	. 0130
16       "       "       10.5       29.9"       23.3       8.51       24,650       .0116         18       "       "       14.7       38.9"       23.1       10.35       29,980       .0114         28       "       "       16.7       3.2" Hg       23.0       11.50       33,310       .0108         30       "       "       21.2       3.9"       23.0       13.34       38,640       .0110         32       "       "       25.2       4.4"       23.0       15.18       43.960       .0101	15	**	· • • • •	9.0	26 5"	20.1	0.00	29,850	. 0116
18       "       "       14.7       38.9"       23.5       0.51       24,050       .0117         28       "       "       16.7       3.2" Hg       23.1       10.35       29,980       .0114         28       "       "       16.7       3.2" Hg       23.0       11.50       33,310       .0108         30       "       "       21.2       3.9"       23.0       13.34       38,640       .0110         32       "       "       25.2       4.4"       23.0       15.18       43.960       .0101	16	**	rt	10 5	29 9"	40.0 99.9	1.04	44,000 94 650	. UIID
28       "       "       16.7       3.2" Hg       23.0       11.50       33,310       .0114         30       "       "       21.2       3.9"       23.0       11.50       33,310       .0108         32       "       "       25.2       4.4"       23.0       15.18       43.960       .0114	18	**	**	14 7	38 011	40.0 99.1	0.01	44, 000	. UII7
30       "       10.7       3.2" Hg       23.0       11.50       33,310       .0108         30       "       "       21.2       3.9"       23.0       13.34       38,640       .0110         32       "       "       25.2       4.4"       23.0       15.18       43.960       0101	28		**	16 7	20.3° 2011 Ha	23.1	10.35	29,980	. 0114
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	30	**	rt .	10. í 91 9	5.4° ng	23.0	11.50	33,310	. 0108
	32	**	11	25.2	3. <del>3</del> 4.4''	23.0 23.0	13.34 15.18	38, 640 43, 960	. 0110 0101

- 40-

\*Air Products Research Notebook No. 25

ł

# TABLE 8

# CROSS PLOT DATA

	N <sub>Re</sub>					$f_s/f_e$				
	· · ·	Grindley & Gibson .009	White 02	Lapin .030	Meier .048	Christensen 049	Christensen . 092	Meier . 100	Meier .125	Lapin . 135
- 41 -	$100 \\ 300 \\ 600 \\ 1,000 \\ 2,000 \\ 10,000 \\ 20,000 \\ 35,000 \\ 50,000 \\ 70,000 $	1.000 0.900 0.769 0.667 0.580	0.971 0.833 0.700 0.591 0.481	0.963 0.944 0.917 0.909	. 842 . 676 . 601 . 492 . 357 . 759 . 742 . 739 . 744 . 742	      	  .729 .714 .693 .685 .685	. 734 . 625 . 504 . 400 . 291 . 664 . 667 . 661 . 659 . 659	. 704 . 544 . 435 . 356 . 259 . 567 . 566 . 563 . 565	 0. 513 0. 518 0. 519 0. 521
			· .				· · ·			
						•				

# SAMPLE CALCULATION

G

Coil 0.100 Tube I.D. = 0.081" Length of tubing = 123" = 10.25" Flow rate = 2.37 std liters / minu Av. temperature in coil =  $72^{\circ}$  F. Inlet pressure to coil = 89.7 psia Pressure drop thru coil = 11.0" Hz Av. pressure = 89.7 - (0.390/2) =Density @ 89.5 psia &  $72^{\circ}$  F. = 0.4Viscosity @ 89.5 psia &  $72^{\circ}$  F. = 0.4Cross-sectional area =  $(6.75 \times 10^{\circ})$ G = G2  $N_{\text{Re}}$  $f_c =$ f<sub>s</sub>/f

rate = 2.37 std liters / minute nitrogen  
temperature in coil = 72° F.  
t pressure to coil = 89.7 psia  
sure drop thru coil = 11.0° H<sub>2</sub>O = .0.390 psi = 56.0 psf  
pressure = 89.7 - (0.390/2) = 89.5 psia  
ity @ 89.5 psia & 72° F. = 0.445 lb/ft3  
osity @ 89.5 psia & 72° F. = 0.445 lb/ft3  
s-sectional area = (6.75 x 10<sup>-3</sup>)<sup>2</sup>x 0.785 = 3.56 x 10<sup>-5</sup> ft<sup>2</sup>  
2.37 l/min x 0.0353 ft<sup>3</sup>/l x 0.073 lb/ft<sup>3</sup> x 1/60 min/sec x  

$$10^{5/3.56$$
 ft<sup>-2</sup> = 2.86 lb/ft<sup>2</sup>-sec  
8.15 lb<sup>2</sup>/ft<sup>4</sup>-sec<sup>2</sup>  
= DG/µ = .00675 ft x (2.86 lb/ft<sup>2</sup>-sec) = 1660  
11.67 x 10<sup>-6</sup> lb/ft-sec  
 $\Delta PDg_{c}\rho/2LQ^{2} = 56.0 lb/ft^{2} x .00675 ft x 32.2 lbm-ft/lbf-sec^{2}x .445
2 x 10.25 ft x 8.15 lb2/ft4-sec2 ft3/lb
= 0.032
 $D = \frac{16/N_{Re}}{f_{c}} = 0.301$   
True Diameter Determination  
 $\Delta P = (4fL/D)[(W^{2}x16/\pi^{2}D^{4} 2g_{c}p)]$   
minar flow f=KN<sub>R</sub> where K = 16 f = KµWD/4W  
straight tube diameter = 0.078"  
 $\Delta P = 4(KµWD/4W)(L/D)((W^{2}x16/\pi^{2}D^{4} 2g_{c}p)] = K(constants)(1/D^{4})$   
 $\frac{\Delta P = K(constants)(1/D^{4})}{\Delta P' = K'(constants)(1/D^{4})}$   
 $\frac{\Delta P = K(constants)(1/D^{4})}{\Delta P' = K'(constants)(1/D^{4})}$$ 

In la From Nomin

w rate = 2.37 std liters / minute nitrogen  
temperature in coil = 72° F.  
et pressure to coil = 89.7 psia  
ssure drop thru coil = 11.0" H<sub>2</sub>O = 0.390 psi = 56.0 psf  
pressure = 89.7 - (0.390/2) = 89.5 psia  
cosity @ 89.5 psia & 72° F. = 11.67 x 10<sup>-6</sup> lb/ft-sec  
ss-sectional area = (6.75 x 10<sup>-3</sup>)<sup>2</sup>x 0.785 = 3.56 x 10<sup>-5</sup> ft<sup>2</sup>  
2.37 l/min x 0.0353 ft<sup>3</sup>/l x 0.073 lb/ft<sup>3</sup> x 1/60 min/sec x  

$$10^{5}/3.56$$
 ft<sup>-2</sup> = 2.86 lb/ft<sup>2</sup>-sec  
= 8.15 lb<sup>2</sup>/ft<sup>4</sup>-sec<sup>2</sup>  
= DG/µ = .00675 ft x (2.86 lb/ft<sup>2</sup>-sec) = 1660  
11.67 x 10<sup>-6</sup> lb/ft-sec  
 $\Delta PDg_{c}\rho/2LC^{2} = \frac{56.0 \ lb/ft^{2} x .00675 \ ft x 32.2 \ lb_{m}-ft/lb_{f}-sec^{2x} .444$   
 $2 x 10.25 \ ft x 8.15 \ lb^{2}/ft^{4}-sec^{2} \ ft^{3}/lt$   
 $= 0.032$   
fc =  $\frac{16/N_{Re}}{f_{c}}$  = 0.301  
True Diameter Determination  
 $\Delta P = (4fL/D)[(W^{2}x16/\Pi^{2}D^{4} 2g_{c}p)]$   
aminar flow f=KN<sub>Re</sub> where K = 16 f = KµWD/4W  
is straight tube data [Fig 11 ] K = 14 (using nominal diameter)  
nal tube diameter = 0.078"  
 $\Delta P = 4(KµWD/4W)(L/D)((W^{2}x16/\Pi^{2D^{4}} 2g_{c}p) = K(Constants)(1/D^{4})$   
 $\frac{\Delta P = K(Constants)(1/D^{4})}{\Delta P' = K'(Constants)(1/D^{4})}$   
where D refers to the nominal diameter  
and D refers to the true diameter  
 $\Delta P = \Delta P'$ , Constants = constants', D/D' =  $\sqrt{K/K}$ 

$$D = 0.078" \sqrt{16/14}$$

۱.

= 0.081"