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UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF MINES HELIUM ACTIVITY HELIUM RESEARCH CENTER

INTERNAL REPORT

CONCERNING PHYSICAL PARAMETERS

FOR USE IN AN ABSOLUTE GAS VISCOSIMETER

BY

R. A. Guereca

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BRANCH	BRANCH	OF FUNDAMENTAL	RESEARCH
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Project 5574

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R. A. Guereca, $\frac{1}{H}$ H. P. Richardson, $\frac{2}{J}$ J. L. Gordon, $\frac{2}{J}$ and J. E. Miller $\frac{2}{J}$

ABSTRACT

Accurate measurements of physical dimensions of a section of stainless steel capillary tubing are presented and used to develop a final working equation for an absolute gas viscosimeter. The effects of pressure and temperature on these dimensions are considered. The internal surface finish and non-uniformity of the capillary bore are discussed as well as entrance, kinetic energy, gas slippage, and gas compressibility correction factors.

INTRODUCTION

The Bureau of Mines Helium Research Center is using a 208-foot long, thick-walled, stainless steel capillary tube, 0.030 inch in internal diameter, wound in the form of a helix 20 inches in diameter,

¹Supervisory Research Chemist, Project Leader, Physical Properties Studies, Helium Research Center, Bureau of Mines, Amarillo, Texas. ²Research Chemist, Helium Research Center, Bureau of Mines, Amarillo, Texas.

Work on manuscript completed July 1966.

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Work on manuscript completed July 1966.

to determine viscosities for pure gases and mixtures at high pressure levels. A coiled capillary of the above dimensions is necessary at high pressures in order to obtain accurately measurable pressure drops at very low volumetric flowrates and to maintain a uniform temperature over the entire length; further, certain correction factors are minimized. Absolute viscosities, reproducible to an accuracy of one micropoise or better, are being evaluated. The values are absolute, insofar as calibration with a gas of known viscosity is not required. Prior to this, a 32-foot long capillary of the same dimensions was used for the experimental determination of steady-state laminar flow boundary conditions applicable to the coiled system.

Accurate measurements of the physical dimensions of a capillary section were made by the Atomic Energy Commission Pantex Plant, Amarillo, Texas. All measurements were taken under controlled environmental conditions.

The intent of this report is to present these measurements, show how they are used in determining certain physical parameters of interest, and develop a viscosity equation which includes corrections for the effects of the temperature and pressure levels on these parameters. The parameters are: mean radius, R_m , of the capillary tubing; variation of individual radii, R_i , with length, L_i ; and total length, L_T .

The correction for non-uniformity of the capillary bore or variations in R along L_T is shown to be negligible through the use of a correction factor, δ . In a later section, the entrance or Couette cor-

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to determine visconities for pure games and mixtures at high pressures is accessary at levels. A colled capillary or the shows dimensions is necessary at high pressures is order to obtain accurately measureble pressures drops at very ine volumetric flowrates and to maintain a uniform temperature over the antire length; forther, certain correction factors are minimized. Absolute viscosities, reproducible to an accuracy of one instant as calibration with a gas of known viscosity is not required. Frior to this, a t2-fort long capillary of the same dimensions was used for the experimental determination at strady-arabe lesions flow homenary accorditions applicable to an accuracy for an accuracy of and insolar as calibration with a gas of known viscosity is not required.

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The correction for non-uniformity of the capillary hore or varia-, tions in A₁ slow by the shown to be negligible through the use of s correction factor, 6. In a later section, the entrance of Coustro cor-

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rection, involving R_m and L_T , is shown to be negligible; the kinetic energy correction, involving R_m^4 when expressed in pressure units, and gas slippage at the walls of the capillary, involving R_m and the mean free path of the molecules, λ , also are shown to be negligible at the pressure and temperature levels of interest. The effect of gas compressibility, which does not involve a direct metrological determination, is discussed and shown to be negligible because of the very low pressure drops in the system.

At a given temperature (T) and pressure (P), the modified Poiseuille equation, incorporating the physical parameters just mentioned, is:

$$\eta = \left[\frac{\pi R_{m}^{4} \Delta P_{e}}{8L_{T} \delta Q_{m}} \right], \qquad (1)$$

where

 η = computed viscosity at (T,P), poises;

- R = mean radius of the capillary tube if the bore
 were uniform throughout, cm;
- △P_e = effective pressure drop used to overcome viscous resistance; measured pressure drop (△P_{me}) corrected for kinetic energy effects, dynes/cm²;

$$L_{T}$$
 = total length of capillary, cm

- δ = correction of actual capillary bore from a uniform, right circular cylinder, dimensionless;
- $Q_m = mean volumetric gas flow rate, cm³/sec, at the mean system pressure, <math>P_m$.

rection, invaluing R_{a} and h_{T} , is shown to be could with the static snargy correction, involving R_{a}^{A} when moresed is measure units, and gas slippings at the value of the capillary, involving R_{a} and the seam free peth at the colocular, λ , also are shown to an multiplic at the pressure and issue recore levels of interest. Therefore of gas conpressibility, which does not involve a direct attractively is ray for them, is discussed and shown to be nightably because of the very low pressure area in the sporta.

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At a given temperature (1) and pressere (2), the modified folesmilie equation, theoryproving the physical parameters (our continued, is:

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for binaric energy effects, dynas/ca², inclusion energy effects, ca², energy energy effects, dynas/ca², inclusion energy energy

A vertical volumetric rate pump circulates gas isothermally through the capillary at a constant mean rate, Q_m ; the pressure drop is measured by a precision-delta-pressure transducer. It is tacitly assumed that any basic errors in Q_m and $\triangle P_{me}$ are negligible. Once the physical parameters R_m , L_T , and δ are known, as well as the effects of temperature and pressure on R_m and L_T , the determination of viscosity basically involves plotting a series of values of $\triangle P_e$ versus Q_m on rectangular coordinates and determining the slope of this straight line.

The necessity for highly accurate and precise physical measurements can be noted from equation (1) where R_m is raised to the fourth power. Assuming all other terms to be correct, if R_m is known to within 5 x 10⁻⁶ inch, the computed viscosity will be within 0.25 micropoise when the true value is of the order of 200 micropoises.

MEASUREMENT PROGRAM

The original measurement program was designed to cross-check R_m by two methods. The "metrometric" method consisted of measurements of out-of-roundness, internal diameters (ID), and internal roughness of 4-inch sections of the capillary. The "volumetric" method included measurements of the length, external diameters (OD), and weights of 12-inch sections. If the density is accurately known and is uniform, the volumetric method can be used to compute the ID of the capillary bore. All measurements were made at 293° K and O psig.

Measurements were taken on a 19-foot section selected at random from 1,000 feet of 347 stainless steel tubing supplied by Superior Tube A vertical volumetric rate put circulates yes isothermally chrough the capillary at a constant man rate, Q_{μ} , the presents drep is measured by a precision-delicitation transducer. It is taulity assumed that any basic verous in Q_{μ} and $B_{\mu\mu}$ are negligible. Once the physical parameters R_{μ} , L_{μ} , and b are bound, as well as the effects of temporature and pressure on R_{μ} and L_{μ} , the determination of viscosity basically theolyes plotting a series of values of B_{μ} versus Q_{μ} on parameters of the series of the determination of viscosity basically theolyes plotting a series of values of B_{μ} versus Q_{μ} on

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The necessity for highly accurate and prediat poysical messurements can be nared from equation (1) where h is related to the farth power. Assuming all other terms to be except, if h is known to sight 5 x 10⁻⁶ inch, the computed viscosity will as within 0.25 micropoles when the true value is pf the order of 200 micropoleds.

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Measurements were taken on a 19-foot section selected at random from 1,000 feet of 347 stainless steel tubing supplied by Superior Tube Company. 3/ This "precision drawn instrument tubing" is nominally 0.122-

³/_{Trade names are used for information only and endorsement by the Bureau of Mines is not implied.}

inch OD and 0.030-inch ID. Average mechanical properties are: 149,500psig ultimate tensile strength and 136,400-psig yield strength.

The 19-foot section was cut into 1-foot lengths for the volumetric program. Each segment was formed into a circular arc with a 10.00000inch radius of curvature, using a special fixture (figure 1) because

Figure 1.-Fixture for length of bore measurements.

the viscosimeter tubing is wound into a 20-inch diameter helix. The length and four OD's were measured for each section. The l-foot lengths were weighed on an analytical balance before being cut into three 4-inch lengths. At each end of the 4-inch samples, three ID's, 60 degrees apart, were measured at a depth of 1/16 inch, and a profile of the outof-roundness was taken at the same depth. The 4-inch samples were held in another fixture (figure 2) constructed to have the same 10.00000-inch

Figure 2.-Fixture for ID measurements and out-of-roundness profiles.

radius of curvature. By the above procedure, a total of 114 out-of-

Company - this "precision drawn instrument taning" is newithily 0.422-

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inch 00 and 0.030-inch in Arciege mechanical properties over 100,300-

program. Each segment par formed into a circular are with a lt.000300. Inch radius of curvatore, using a special fixture (figure 1) bacance

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Figure S. -Fiszence for ID measurements, and gue-of-roundness profiles.

redius of corvince. By the share procedure, a coral of 114 cor-of-



FIGURE I.-Fixture for Length of Bore Measurements







roundness profiles and 342 ID measurements was made. Six of the 4-inch lengths were randomly selected for longitudinal internal finish or surface roughness measurements.

The desired lengths were cut with a saw and the ends ground smooth and square with a surface grinder to minimize distortion and provide a smooth reference surface. The surface grinder also was used to expose the inner surface for internal roughness determinations. A microscope was used to examine exposed internal surfaces. No evidence of distortion was found at the measurement depth. The out-of-roundness apparatus also was used to examine cross section profiles at various depths and showed no evidence of distortion due to cutting. Figure 3 shows a longitudinal

Figure 3.-Longitudinal view of capillary internal surface.

view of the internal surface; figure 4 shows end views of the capillaries.

Figure 4.-End view of capillary bores.

MEASUREMENTS AND EQUIPMENT PRECISION AND ACCURACY CAPABILITY

The ID's were measured with a Societe Genevoise D'Instruments De Physique Universal Measuring Machine, Model MU-214B, called the "SIP." A special gaging stylus, 0.005 inch in radius, was fabricated and used in conjunction with the holding fixture which vertically supported the capillary sections. Individual diameters measured with this instrument

roundmens profiles and 342 15 mensurements was made. Six of the 4-inch lengths were randomly selected for longitudinal internal finish or sur-

The desired lengths were cut with a set and the star prove another and square with a surface grinder is similate distortion and provide a sumpth reference sortage. The surface grinder size was used to expose the inner surface for internal rowanness determinations. A microscope and used to examine explained internal surfaces, the evidence of discortion was found at the measurement depth. The put-of-containers programme also and used to examine cross section profiles at various depths and showed and used to examine cross section profiles at various depths and showed and used to examine cross section profiles at various depths and showed

Figure 3.-Langicadinal view of copilipiv internal succare.

view of the incornal surface; figure 4 shows and views of the replicatios.

Figure 4 .- 2nd view of capiblory bornd

AND ACCOMACY CAPABILITY

une LD's were measured with a prototic copression of colled the "SIP." Physique Universal Messuring Machine, Model MU-2103, colled the "SIP." A special seging stylus, 0.005 inch in radius, was fahricated and used in conjunction with the holoing flature which vertically supported the ceptilary sections. Individual diameters measured with this instrument



FIGURE 3.- Longitudinal View of Capillary Internal Surface





FIGURE 4.- End View of Capillary Bores



were conservatively estimated to be accurate within 20×10^{-6} inch and precise within 10×10^{-6} inch. The error of measurement includes possible inaccuracies in stylus deflection, internal surface finish, and the stylus tip contacting the inner surface. Results of the ID measurements are presented in table 1 and include the average radius for each section obtained from the 0°, 60°, and 120° SIP measurements; each 4-inch length had a reference mark on both ends to represent the 0° angle. The average radius from all SIP measurements is 0.015199 inch and is considered to be accurate to within 10 microinches, corresponding to a computed viscosity within 0.5 micropoise.

Cross section or out-of-roundness profiles were taken with an Engis Equipment Company "Talyrond" Machine manufactured by Taylor, Taylor, and Hobson (Leicester, England). A special gaging stylus of approximately the same dimensions as the SIP stylus was used in the Talyrond instrument. The capillary tubes were held on the Talyrond in the same fixture utilized for SIP internal diameter measurements. The reference mark identified the Talyrond charts with the SIP measurements. The accuracy of the Talyrond is 3×10^{-6} inch, according to standards certified by the Atomic Energy Commission Primary Standards Laboratory (ALO), Albuquerque, New Mexico. This instrument charts deviation of the bore from a perfect circle on a greatly expanded scale. Three typical Talyrond charts are shown in figures 5, 6, and 7 and show, respectively, circular, trilobular, and irregular

Figure 5.-Cross section profile of a circular capillary bore.

were conservatively mainstud to be accurate within 20 % 10 ° inch and precise within 10 x 10⁻⁶ inct. The error of manuframent includes possible insecuration in static definition, internal sorfare finish, and the status tip contacting the femic surface. Semults of the 13 menuframits are presented in table 1 and include the second costs for tack contraction obtained from the 0°, 00°, and 130° 537 memorynamics, each 4-fees langth had a references mark as both such to represent the 14 remelerate to be securing in the contaction of action to costs for the second second from all file memorynamic is 0.013199 (set) and is remelerate to be securate is within 10 memorynamic at 0.013199 (set) and is remelerated to be securted. Subscreption for the second sector of the securation of the second second second second second second second of a state points of a second se

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Figure 3.-Cross section profile of a circular aspillary bore.

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Sample number		Internal diameter, inch					
	0°	60°	120°				
		() . (
1-1-A	0.03046	0.03045	0.03048	0.015232			
1-1-B	.03057	.03049	.03041	.015245			
2-1-A	.03039	.03035	.03044	.015197			
2-1-B	.03051	.03041	.03031	.015205			
3-1-A	.03039	.03040	.03041	.015200			
3-1-B	.03045	.03046	.03043	.015223			
				.015217			
1-2-A	0.03041	0.03043	0.03048	0.015220			
1-2-B	.03030	.03044	.03046	.015200			
2-2-A	.03046	.03050	.03048	.015240			
2-2-B	.03050	.03045	.03056	.015252			
3-2-A	.03048	.03051	.03054	.015255			
3-2-B	.03055	.03051	.03046	.015253			
				.015237			
1-3-A	0.03033	0.03035	0.03044	0.015187			
1-3-В	.03058	.03052	.03046	.015260			
2-3-A	.03047	.03043	.03054	.015240			
2-3-В	.03044	.03049	.03042	.015225			
3-3-A	.03043	.03039	.03030	.015187			
3-3-В	.03043	.03031	.03035	.015182			
				.015214			
1-4-A	0.03031	0.03029	0.03030	0.015150			
1-4-B	.03039	.03035	.03038	.015187			
2-4-A	.03045	.03039	.03038	.015203			
2-4-B	.03041	.03037	.03038	.015193			
3-4-A	.03032	.03040	.03031	.015172			
3-4-B	.03041	.03045	.03043	.015215			
				.015187			
1-5-A	0.03031	0.03036	0.03032	0.015165			
1-5-B	.03040	.03039	.03038	.015195			
2-5-A	.03045	.03039	.03041	.015208			
2-5-B	.03038	.03041	.03036	.015192			
3-5-A	.03045	.03046	.03039	.015217			
3-5-В	.03043	.03035	.03038	.015193			
6				.015195			

TABLE 1. - Internal diameter measurements

	C-BUER E		
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TABLE I. - Internet diamater measurements

.015135

Sample number	I	Internal diameter, inch					
	0°	60°	120°				
1-6-A	0.03036	0.03041	0.03043	0.015200			
1-6-B	.03031	.03032	.03034	.015162			
2-6-A	.03042	.03040	.03045	.015212			
2-6-В	.03045	.03043	.03043	.015218			
3-6-A	.03043	.03041	.03040	015207			
3-6-B	.03037	.03034	.03036	.015178			
				.0	15196		
1-7-A	0.03036	0.03033	0.03031	0.015167			
1-7-B	.03041	.03032	.03036	.015182			
2-7-A	.03042	.03036	.03039	.015195			
2-7-B	.03038	.03037	.03041	.015193			
3-7-A	.03042	.03046	.03037	.015208			
3-7-B	.03040	.03043	.03042	.015208			
				.0	15192		
1-8-A	0.03038	0.03042	0.03042	0.015203			
1-8-B	.03043	.03037	.03038	.015197			
2-8-A	.03038	.03039	.30336	.015188			
2-8-В	.03045	.03047	.03046	.015230			
3-8-A	.03046	.03048	.03045	.015232			
3-8-B	.03047	.03044	.03041	.015220			
				.0	15212		
1-9-A	0.03050	0.03041	0.03038	0.015215			
1-9-B	.03039	.03036	.03042	.015195			
2-9-A	.03047	.03041	.03045	.015222			
2-9-В	.03043	.03046	.03037	.015210			
3-9-A	.03044	.03037	.03035	.015193			
3-9-В	.03040	.03045	.03044	.015215			
				.0	15208		
1-10-A	0.03046	0.03043	0.03040	0.015215			
1-10-B	.03045	.03040	.03042	.015212			
2-10-A	.03037	.03038	.03035	.015183			
2-10-B	.03043	.03044	.03042	.015215			
3-10-A	.03040	.03037	.03041	.015197			
3-10-В	.03044	.03040	.03041	.015208			
				0	15205		

TABLE 1. - Internal diameter measurements - Continued

		20037		
				8-8-8

Sample number	I	nternal diameto	er,	Average <u>radius, inch</u>
	0°	60°	120°	
1-11-A	0.03040	0.03036	0.03038	0.015190
1-11-B	.03039	.03041	.03037	.015195
2-11-A	.03039	.03034	.03036	.015182
2-11-В	.03038	.03041	.03037	.015193
3-11-A	.03040	.03041	.03038	.015198
3-11-В	.03041	.03039	.03041	.015202
				.015193
1-12-A	0.03036	0.03036	0.03035	0.015178
1-12-B	.03034	.03038	.03037	.015182
2-12-A	.03036	.03034	.03033	.015172
2-12-B	.03026	.03022	.03020	.015113
3-12-A	.03038	.03035	.03033	.015177
3-12-B	.03035	.03033	.03032	015167
				.015165
1-13-A	0.03031	0.03034	0.03032	0.015162
1-13-В	.03035	.03040	.03035	.015183
2-13-A	.03038	.03034	.03040	.015187
2-13-В	.03040	.03043	.03042	.015208
3-13-A	.03036	.03042	.03037	.015192
3-13-В	.03042	.03040	.03042	.015207
				.015190
1-14-A	0.03038	0.03041	0.03039	0.015197
1-14-B	.03039	.03043	.03042	.015207
2-14-A	.03044	.03043	.03045	.015220
2-14-B	.03045	.03043	.03046	.015223
3-14-A	.03045	.03044	.03042	.015218
3-14-B	.03044	.03046	.03043	.015222
				.015214
1-15-A	0.03045	0.03048	0.03046	0.015232
1-15-B	.03041	.03044	.03047	.015220
2-15-A	.03042	.03042	.03045	.015215
2-15-B	.03040	.03040	.03041	.015202
3-15-A	.03040	.03044	.03044	.015213
3-15-B	.03045	.03045	.03042	.015220
				015217

TABLE 1. - Internal diameter measurements - Continued

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TABLE 1. - Internal dismacht owners - Concined

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Sample number		Internal diameter inch	Internal diameter, inch		
	0°	60°	120°		
1-16-A	0.03041	0.03044	0.03045	0.015217	
1-16-B	.03045	.03042	.03040	.015212	
2-16-A	.03046	.03047	.03045	.015230	
2-16-B	.03046	.03043	.03043	.015220	
3-16-A	.03043	.03041	.03042	.015210	
3-16-в	.03040	.03037	.03040	.015195	
				. (015214
1-17-A	0.03040	0.03039	0.03042	0.015202	
1-17-В	.03043	.03042	.03040	.015208	
2-17-A	.03045	.03044	.03046	.015225	
2-17-B	.03041	.03039	.03040	.015200	
3-17-A	.03034	.03038	.03033	.015175	
3-17-В	.03032	.03035	.03035	.015170	
				.(015197
1-18-A	0.03037	0.03034	0.03033	0.015173	
1-18-B	.03039	.03037	.03037	.015188	
2-18-A	.03033	.03037	.03038	.015180	
2-18-B	.03037	.03035	.03024	.015160	
3-18-A	.03033	.03030	.03028	.015152	
3-18-В	.03034	.03031	.03031	.015160	
				. (015169
1-19-A	0.03041	0.03036	0.03038	0.015192	
1-19-В	.03033	.03024	.03026	.015138	
2-19-A	.03034	.03032	.03023	,015148	
2-19-B	.03027	.03030	.03034	.015152	
3-19-A	.03030	.03029	.03034	.015155	
3-19-В	.03031	.03032	.03032	.015158	
			1		015157

TABLE 1. - Internal diameter measurements - Continued

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TABLE 1. - Integrand discover to later - Continued

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FIGURE 5.-Cross Section Profile of a Circular Capillary Bore

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FIGURE 6.-Cross Section Profile of a Trilobular Capillary Bore



Sample number	Internal diameter, inch					
	0.	<u> 60 ° </u>	120°			
3-2-A	0.03048	0.03051	0.03054			

Talyrond



FIGURE 7. - Cross Section Profile of an Irregular Capillary Bore



FIGURE T. - Cross Section Proving of an Preputar Supillary Bard

Figure 6.-Cross section profile of a trilobular capillary bore. Figure 7.-Cross section profile of an irregular capillary bore.

profiles. It is not necessary that the work be accurately centered in order to show true deviations from roundness.

Each Talyrond chart division represents 50 x 10⁻⁶ inch, reproducible to approximately the width of the trace. The magnification normal to the curved surface being charted is much greater than the magnification along the circumference. Because the normal magnification is 2,000, the Talyrond profiles are very close to being circular in spite of the "trilobular" appearance of figure 6. To illustrate further, the 1inch scale of a chart represents the outer one inch of a 5-foot diameter circle.

The OD's were measured with a Pratt and Whitney Standard End Measuring Machine certified accurate by the manufacturer to 5×10^{-6} inch per inch. The ALO Metrology Laboratory also maintains and certifies the instrument on a periodic basis to the same specification. Four OD's were determined for each 1-foot section, two at each end, 90 degrees apart. It was necessary to place a cylinder between the sample and the anvil of the end-measuring machine to obtain point contact. The certified dimension of the cylinder, accurate to 5×10^{-6} inch, was subtracted from each reading to obtain the OD values listed in table 2. The apparent accuracy of the OD's is 10×10^{-6} inch. The average OD computed from all measurements is 0.122020 inch.

Eigure 6. -Cross section profile of a trilobular cepillary sore.

profiles. It is not necessary that the work he accurately rentered in order to show true devisitons from roundness.

Lack fairead that director represents fills 10 (ach, openducible to approximately the which of the space the manification normal to the convect surface only observed is much greater than the mapnification stong the circumburence service the much greater than the map-2,000, the "high of the circumburence service to being eracher to be of the "fritubutur" spacetones of from a for this open for the of the transmore of from a for the open for the state of the transmore of from a for this open for the open for the the transmore of from a for the open for the open for the open included as a state represente the open and the open for the open circus.

The DD's were as acced with a Brett and Mitthes Standard and Medainiting Machine serviced accounce by the semialatrice to 2 a 10⁻² last per inch. The ALD Metri are includered at the metricities of certifies the instrument on a periodic on the total sector area of [footion. The DD's sector of the end accessory in the sector area of [footion. The DD's adait, if the endescentric archive to the end of the sector of the sector adait of the end accessory in the courter to 3 a 10⁻⁰ and an sector of the end accessory in the courter of the sector of the sector field discontant of the cylinary archive to the point counter. The sector from each reading to the OF's is 10 a 10⁻⁰ littly. The sector of respected the ant sectored is the OF's is 10 a 10⁻⁰ littly. The sector of the sector of the all measurements in 0,122300 littly.

Sample <u>nu</u> mber	0	utside diam	eter, inch		Average
1	0.12214	0.12214	0.12203	0.12203	0.122085
2	. 12210	. 12202	. 12212	. 12208	.122080
3	.12209	. 12207	. 12212	.12211	.122098
4	.12210	.12206	. 12215	.12207	.122095
5	.12197	. 12205	.12206	.12206	. 122035
6	.12211	. 12197	. 12214	.12199	. 122052
7	.12192	.12180	.12205	.12195	.121930
8	.12202	.12199	.12212	.12200	. 122032
9	.12202	. 12200	.12203	. 12199	. 122010
10	. 12200	.12195	. 12204	.12201	. 122000
11	.12211	.12196	.12203	. 12196	.122015
12	.12204	.12205	. 12210	.12205	.122060
13	. 12206	.12197	.12203	.12201	. 122018
14	. 12204	. 12195	.12213	. 12209	. 122052
15	.12202	.12199	. 12195	.12194	.121975
16	. 12189	.12199	. 12213	.12202	. 122008
17	.12180	.12186	.12204	. 12195	. 121912
18	. 12200	. 12187	. 12212	. 12191	. 121975
19	. 12195	.12201	.12193	.12190	.121948

of the sector is disconting

TABLE 2. - External diameter measurements

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CASEL 3 - BECANNEL STANDINE, MEANING - C. ILCAY

The 1-foot sections were weighed on a 2-kilogram capacity analytical balance to 0.1 milligram. The National Bureau of Standards method of transposition $(\underline{8})^{\underline{4}/}$ was used with certified stainless steel standard

4 Underlined numbers in parentheses refer to items in the list of references at the end of this report.

weights. Results of the weighings are given in table 3. The average apparent mass versus brass is 1.420717 grams per inch with an average deviation of ± 0.00041 .

The lengths of the 1-foot sections are given in table 3. With a section placed in the fixture (figure 1), a "best size" measuring wire was inserted in each end of the tube to establish the true centerline. The SIP optical system was used to measure the chord length from the center of the bore at one end to the center of the bore at the other end. The arc length (length of bore) was computed from:

$$L = \frac{\pi (10.00000 + a) \theta}{180} , \qquad (2)$$

where "a" is one-half the average OD of the bore, and θ is the angle of the sector in degrees.

Longitudinal internal surface finish measurements were taken with a Taylor, Taylor, and Hobson "Talysurf" Surface Finish Measuring Machine, which charted both surface finish and waviness relative to a 1-microinch optically-flat reference master. The readout capability of this instrument is 5 \times 10⁻⁷ inch with interpolation to 1 \times 10⁻⁷ inch The 1-foot sections were weighed on a 2-kilogene capacity analyst del balance to 0.1 milidgram. The Astional Bureau of Standards method of transporttion (812 tos used with certifics stainless steel standard

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weights. Meanite of the weighings are given in rable in the secrego apparent mass verser broas is 1.420717 grows put in h with an merage

The largents of the 1-foot satisfies are given in this 2. With a section placed is the fixture (ligure 1), a "satisic" as coning the was incorted in each and of the tote of establish the cross concerting, the SIP optical apatem day used to measure the chord length true the center of the bure at one and the fix concertic of the bord length true the end. The ure length flored of hore) was computed for a the other

$$\Gamma = \frac{\pi (10.00000 + 3) \%}{180}, \qquad (2)$$

where "a" to one-half the average 00 of the bare, and a to the ongle of the sector in degrees.

Longitudiual internal surface finish pessatements were taken with a Taylor, Taylor, and Nobion "Talyeds?" Surface Finish Measuring Machine, which charned bolk surface fisish and waviness relative to a 1:microtach optically-flat reference messer. The readout caushility of this instriment is 5 x 10⁻⁷ toch with interpolation to 1 x 10⁻⁷ inch

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	Length	Length	Apparent	
Sample	(chord),	(arc),	mass vs	True mass,
number	in	in	brass, g	g
1000	11 225/2	11 00840	16 03/05	16 93/17
1	19212	05627	16 95923	16 85835
2	. 10215	.07700	17.001(0	17 00100
3	.28229	.97709	17.02168	17.02180
4	.21809	.89966	16.91229	16.91241
5	.24830	.93607	16.95357	16.95369
6	.24382	.93067	16.94858	16.94870
7	.21662	.89790	16.89985	16.89997
8	.23920	.92510	16.94461	16.94473
9	.19920	.87692	16.87065	16.87077
10	.22077	. 90289	16.91059	16.91071
11	.21817	.89976	16.90626	16.90638
12	. 19385	.87047	16.86611	16.86623
13	.22249	. 90496	16.90857	16.90869
14	.20648	.88568	16.88125	16.88137
15	.23230	.91679	16.91755	16.91767
16	.21202	.89235	16.89588	16.89600
17	. 19275	.86916	16.86279	16.86291
18	.21400	.89474	16.88976	16.88988
19	.17942	.85312	16.83715	16.83727

TABLE 3. - Length and mass measurements

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ediare at ho-degree intervale. Only division of a cherr scale is it is not, and concernents 50 - 10⁻¹ inch a coal travel by the between splue. The charr disarter at "bottom of scale" is the failer. The splue distributes at hortees of coals" are determined at each term incore (0⁻, 50⁻, 120⁻) by momenting the distance spaces dis core; and dividing by 0 1 inch put division to get the number of charr division of dividing by 0 1 inch put division to get the number of charr division and dividing by 0 1 inch put division to get the number of charr division at corresponding to 0.000005 and in determining "equivalence distance and corresponding to 0.000005 and in determining "equivalence distance

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along 1/4-inch lengths of exposed surface. The accuracy of surface finish measurements is considered one microinch, including procedural and calibration errors. Arithmetically averaged internal surface roughnesses were five, eight, six, eight, eight, and six microinches. Any minor projection or burr in the capillary wall which is less than 10 microinches will not measurably affect the laminar flow profile.

CONFIRMATION OF MEAN RADIUS THROUGH TALYROND CHARTS

The Talyrond measures out-of-roundness, not actual diameter. The determination of an average "cross sectional" radius from a Talyrond chart depends on relating the chart scale to the diameters measured directly with the SIP. This was accomplished using the SIP reference 0° mark at each end of the 4-inch sections. When the sections were run on the Talyrond, each chart was marked at 0°, 60°, and 120°. In figure 5, "bottom of scale" is the inner circle from which the chart scales radiate at 30-degree intervals. Each division of a chart scale is 0.1 inch, and represents 50 x 10^{-6} inch actual travel by the Talyrond stylus. The chart diameter at "bottom of scale" is two inches. The "equivalent distance at bottom of scale" was determined at each known diameter (0°, 60°, 120°) by measuring the distance across the chart trace, subtracting the chart diameter at "bottom of scale" (two inches), and dividing by 0.1 inch per division to get the number of chart divisions. The accuracy of measuring the distance across the chart was 0.01 inch corresponding to 0.000005 inch in determining "equivalent distance at bottom of scale" and is well within the accuracy of the SIP. The

sion projection of exposed surface. The acoursey of aution finish manshreasents is consulated one effectives, including provideral and calibration errors. Arithmetically everaged internal surface rough masses were liver signs, six, wight, signs, and all storetocks. An along projection of burn to the capillary well which is less than 10 microclosine will not measurably affect the instance fine module.

CONFERNATION OF MANN MADIUS.

chart divisions were converted to actual inches by multiplying by 50 x 10⁻⁶ inch per division. This number was subtracted from the corresponding measured SIP diameter to give "equivalent diameter at bottom of scale." The "equivalent radius at bottom of scale" for each Talyrond chart is the average of the three "equivalent diameters," divided by two.

The area enclosed by the line traced on the chart was measured with a planimeter calibrated in square inches. The radius of a true circle having the same area was computed; the chart radius at bottom of scale (one inch) was subtracted from the computed radius, and the remainder was converted to chart divisions (0.1 inch = one division). The chart division value was converted to actual inches (times 50 x 10^{-6}) and added to the "equivalent radius at bottom of scale." This procedure gave an average radius for each of the 114 cross sections as shown in table 4. The average of all cross sections is 0.015201 inch, which compares very favorably with the 0.015199 inch SIP average and provides confirmation of the SIP diameters. A sample calculation follows for Talyrond chart sample 1-1-B (figure 5).

Equivalent distance at bottom of scale:

 $0^{\circ}:3-25/64$ in - 2 in = 1.391 in = 13.91 div = 0.000695 in; $60^{\circ}:3-5/16$ in - 2 in = 1.312 in = 13.12 div = 0.000656 in; $120^{\circ}:3-5/16$ in - 2 in = 1.312 in = 13.12 div = 0.000656 in.

Equivalent diameter at bottom of scale:

 $0^{\circ}: 0.03057(SIP) - 0.000695 = 0.029875$ in;

 $60^{\circ}: 0.03049(SIP) - 0.000656 = 0.029834$ in;

chart districts ware concerned to signal inches by multiplying by 30 -10⁻⁶ inch per division. This comber was addirected some the corrisoneding measured bit frameter to give "equivalent diseases at bottom of etair." The "equivalent redium at bottom of and." for each tairected that is one private at the shife inches at bottom of

the area an track by the time treest in the chart we may used with a character calthreated to square taches. The ratius of a true clouds been go and include the sequence tend that radius of notion of scale (and ince) are taberisced from the compared ratius, and the fevelocity are converted to chart divisions (0.1 beth a use sivilation). The chart division value was converted to accurd tamines (times 10 a 10⁻⁵) and anded to the "quintum radius at bortain of scale." This procedure gave as specing radius for asch of the 114 errors southers as shown in table 4. The specing of all errors metroins to 0.041200 tanks which confirmation of the Sil errors metroins to 0.041200 tanks which there are the first discourse of all errors metroins to 0.041200 tanks which confirmation of the Sil discourse. A sample calculation talents for the set of the single 1.1-3 (tigure 1).

Taulysiane discence as baccas of scales

0°:3-25/64 in - 2 in * 1.321 in = 13.91 div = 0.005095 in 60°:3-5/15 in - 2 in = 1.312 in * 13.12 div = 3.005696 in 120°:3-5/16 in - 2 in = 1.512 in * 13.12 div = 0.000656 in doutvalant diameter at bottom of scale 0°:0:03057(312) - 0.000655 = 0.0229375 in 60°:0.030649(512) - 0.000656 = 0.0229376 in

0.5

Sample number	Talyrond radius, inch	Last 3 digits of average SIP	Sample number	Talyrond radius, inch	Last 3 digits of average SIP
1-1-A 1-1-B 2-1-A 2-1-B 3-1-A 3-1-B	0.015234 .015237 .015193 .015200 .015195 .015218	232 245 197 205 200 223	1-2-A 1-2-B 2-2-A 2-2-B 3-2-A 3-2-B	0.015220 .015194 .015244 .015242 .015274 .015272	220 200 240 252 255 253
A	Average.015213	217	Ave	rage .015241	237
1-3-A 1-3-B 2-3-A 2-3-B 3-3-A 3-3-B	.015259 .015246 .015215 .015172 .015182 .015209	260 240 225 187 <u>182</u> 214	1-4-B 2-4-A 2-4-B 3-4-A 3-4-B	.015206 .015200 .015196 .015175 <u>.015204</u> .015187	187 203 193 172 <u>215</u> 187
1-5-A 1-5-B 2-5-A 2-5-B 3-5-A 3-5-B	0.015156 .015202 .015216 .015187 .015214 .015202 .015197	165 195 208 192 217 <u>193</u> 195	1-6-A 1-6-B 2-6-A 2-6-B 3-6-A 3-6-B	$\begin{array}{c} 0.015200\\ .015176\\ .015210\\ .015224\\ .015222\\ .015186\\ .015203\end{array}$	200 162 212 218 207 <u>178</u> 196
1-7-A 1-7-B 2-7-A 2-7-B 3-7-A 3-7-B	0.015193 .015196 .015200 .015203 .015214 <u>.015217</u> .015204	167 182 195 193 208 <u>208</u> 192	1-8-A 1-8-B 2-8-A 2-8-B 3-8-A 3-8-B	0.015214 .015195 .015202 .015239 .015238 .015235 .015220	203 197 188 230 232 <u>220</u> 212
1-9-A 1-9-B 2-9-A 2-9-B 3-9-A 3-9-B	0.015226 .015203 .015230 .015221 .015187 .015226 .015215	215 195 222 210 193 <u>215</u> 208	1-10-A 1-10-B 2-10-A 2-10-B 3-10-A 3-10-B	0.015212 .015208 .015194 .015207 .015207 .015210 .01 5 206	215 212 183 215 197 <u>208</u> 205

TABLE 4. - Radii computed by integrating the Talyrond charts

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			023878.4		
0. 1	Talyrond	Last 3		Talyrond	Last 3
Sample	radius,	digits of	Sample	radius,	digits of
number	<u></u>	average SIP	number	<u>inch</u>	average SIP
1-11-A	0.015201	190	1-12-A	0.015171	178
1-11-B	.015202	195	1-12-B	.015199	182
2-11-A	.015183	182	2-12-A	.015177	172
2-11-B	.015200	193	2-12-B	.015112	113
3-11-A	.015218	198	3-12-A	.015181	177
3-11-B	<u>.015195</u>	<u>202</u>	3-12-B	.015176	167
	.015200	193		.015170	165
1-13-A	0.015168	162	1-14-A	0.015199	197
1-13-В	.015176	183	1-14-B	.015201	207
2-13-A	.015174	187	2-14-A	.015239	220
2-13-В	.015221	208	2-14-B	.015235	223
3-13-A	.015195	192	3-14-A	.015213	218
3-13-В	.015215	207	3-14-B	.015239	222
	.015192	190		.015221	214
1-15-A	0.015233	232	1-16-A	0.015222	217
1-15-B	.015223	220	1-16-B	.015214	212
2-15-A	.015229	215	2-16-A	.015223	230
2-15-B	.015218	202	2-16-B	.015225	220
3-15-A	.015210	213	3-16-A	.015190	210
3-15-В	.015232	220	3-16-B	.015185	195
	.015224	217		.015210	214
1-17-A	0.015205	202	1-18-A	0.015175	173
'1-17 - В	.015216	208	1-18-B	.015190	188
2-17-A	.015226	225	2-18-A	.015173	180
2-17-B	.015199	200	2-18-B	.015172	160
3-17-A	.015176	175	3-18-A	.015154	152
3-17-B	.015173	170	3-18-B	<u>.015171</u>	160
	.015199	197		.015172	169
1-19-A	0.015189	192			
1-19-B	.015144	138			
2-19-A	.015124	148			
2-19-B	.015143	152			
3-19-A	.015154	155			
3-19-В	.015167	158			
	015154	157			

TABLE 4. - <u>Radii computed by integrating the Talyrond charts</u> Continued

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TABLE 4 - 20111 combuted by incess (this top, Failyerond cheric

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 $120^{\circ}: 0.03041(SIP) - 0.000656 = 0.029744$ in;

Average = 0.029818 in.

Equivalent radius at bottom of scale = 0.014909 in. Area measured by planimeter = 8.62 in^2 . Radius of circle with same area = $(8.62/\pi)^{1/2}$ = 1.656 in; 1.656 - 1.000 = 0.656 in = 6.56 chart div; $(6.56 \text{ chart div})(50 \times 10^{-6} \text{ in/div}) = 0.000328$. Average radius of cross section (1-1-B) = 0.014909 + 0.000328; = 0.015237 in.

Average radius of three (1-1-B) SIP measurements = 0.015245.

CORRECTION FOR NON-UNIFORMITY OF CAPILLARY BORE

Capillary tube viscosimeters can be considered as an infinite number of uniform, right circular cylinders arranged in series. This concept leads to correcting the hypothetical mean radius, R_m , in equation (1) to approximate more closely the real case and has been discussed by Barr (<u>1</u>, p. 61), Flynn (<u>3</u>, p. 25), Giddings (<u>4</u>, p. D-8), Lemaire (<u>7</u>, p. 21), and Swindells and coworkers (<u>10</u>, p. 17). This report designates the correction as

$$\delta = \frac{\sum_{i=1}^{n} {\binom{R_{m}}{R_{i}}}^{4}}{n} = \frac{\sum_{i=1}^{n} {\binom{L_{i}}{R_{i}}}}{{\binom{L_{T}}{R_{m}}}}, \qquad (3)$$

where L_i is a constant or $L_i = L_1 = L_2 = L_3 = \cdots = L_n$. Ideally, n is infinite. In the practical case, however, n can be some finite number

120":0.03043(51P) - 0.000556 = 0.079244 Tat

Average radius at section of 0.029818 in Iquivalant readius at bottom of scale = 0.024300 in. Area measured by plantaneor = 8.02 m² andtus of strate with ande area = (5.61%)^{1/2} = 1.038 m; (5.56 . 1.000 = 0.6556 in = 5.16 thart atc. (6.56 . are divid50 = 10⁻⁶ in/div) = 0.000016. Average radius of strate section (1-1-5) = 0.014900 + 0.000016.

BARRENTON FOR NON-UNEFORMETY OF CAPELLARY SURE

trailier right verterevers can be considered as an initial mader of matters, right executer cylladors arranged in series. This concept leads to correcting the hypothetical mean radius, R_{μ} , is equation (1) to approximate more closely the real case and has been discrimed by Barr (1, p. 61), Fiyma (2, p. 35), Goldings (4, p. 0-5), freetict (4, p. 21), and satudalle and concessor (60, p. 17). This surger designates the correction on

where he is a nonation, or he - for he was he some Einste number

of samples whereby the evaluation of δ and its insertion into equation (1) may or may not be of significance in computing viscosity, depending on the magnitude of the non-uniformity of the capillary bore. Utilizing the 114 individual SIP radii leads to a value for δ of 1.000030; δ equals 1.000035 using the individual Talyrond radii. In either case, the error in computing viscosity is less than 0.01 micropoise when the viscosity is 200 micropoises.

In computing δ from the average radii tabulated in table 1, the following procedure was used. For sample 1-1-A, the front end of the first 4-inch sample, the average radius of 0.015232 inch was assumed to apply to the first two inches; the average radius for the back end (1-1-B) of this same 4-inch sample, 0.015245 inch, was assumed to apply to the other two inches of this sample. In other words, each averaged radius in table 1 represents a uniform bore of 2-inch length, L_i .

Figure 8 shows the deviation of the 19-foot capillary bore from the

Figure 8. -Deviation of the capillary bore from the average radius.

average SIP radius, R_m , in millionths of an inch. The plotted values are the 1-foot averages shown in the last column of table 1; the maximum deviation is about 40 millionths of an inch.

Figure 9 is a frequency distribution graph of the 342 SIP diameter

Figure 9.-Distribution of SIP diameter measurements.

Aut etable 1-1-1V' che



FIGURE 8.-Deviation of the Capillary Bore from the Average Radius









measurements. Two normal curves are superimposed for comparison; one has the same maximum ordinate and the other has the same average deviation as the measurements. The measurements do not have a normal distribution, but are slightly skewed. As can be seen in figure 8, the deviations are actual variations in the radius rather than a lack of measurement precision and accuracy. This causes the frequency curve for the measurements to be broader than the normal curve with the same maximum ordinate.

PRESSURE AND TEMPERATURE LEVEL EFFECTS ON MEAN RADIUS AND CAPILLARY LENGTH

R_m was determined at 0 psig and 293° K. The increase in R_m with increasing internal pressure can be either computed or physically compensated by the application of an external pressure to the capillary tube.

The increase in R_m with internal pressure was computed by application of the formula for deformation of a long, open-end cylinder given by Timoshenko (11, p. 210):

$$\frac{\left[\triangle R_{m}\right]}{\left[R_{m}\right]}_{(P=0,T)} = \frac{P}{E} \left[\frac{R_{2}^{2} + R_{m}^{2}}{R_{2}^{2} - R_{m}^{2}} + \mu\right], \quad (4)$$

where R_2 is the mean outer radius, at a pressure of 0 psig and a temperature of 293° K; P is the internal pressure in psig; E is Young's modulus; and μ is Poisson's ratio, a constant equal to 0.3 up to the elastic limit. Expressed as a function of pressure and temperature, R_m is:

$$\begin{bmatrix} R_{m} \end{bmatrix}_{(P,T)} = \begin{bmatrix} R_{m} \end{bmatrix}_{(P=0,T)} \begin{bmatrix} 1 + \beta P \end{bmatrix}, \quad (5)$$

measurements. Two normal curves are sureringened for comparison; one has the same maximum ordinate and out other has the tags overage deviaclear as the measurements. The resourcements do not have a normal distribumean but are slightly abored. At can be seen in figure 8, the deviations are metanic variations in the redius nother than a tech of monourcement arestained and accuracy. This redius nother that a tech of monourcement arestained and accuracy. This cannot be seen in figure 6, the deviations to be preader than the normal curve orch the same astimum ordinates.

PRESSURE ARX INC. FOR STAR ENVEL EFFERTS

A var deveration at 0 paig and 200 k. The increase is % with increasing internal pressure can be stimer command of physically companested by the sophication of an vectornal pressure to the simility tube. The increase in R with incernal pressure was command on application of the formula for definition of a long, command cylicsue given

where R₂ is the mean autor cabius, at a presence of 0 paty and a fearperature of 203° K; P is the internal probater to paty, E is Young's codulus; and h is Potseon's ratio, a croatant mouse to 0.5 up to the electic limit, Supressed as a function of processor and emperature. R

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where β , the pressure expansion coefficient, is:

$$\beta = \frac{1}{E} \left[\frac{R_2^2 + R_m^2}{R_2^2 - R_m^2} + \mu \right].$$
 (6)

Also,

$$\begin{bmatrix} R_{m} \end{bmatrix}_{(P=0,T)} = \begin{bmatrix} R_{m} \end{bmatrix}_{(P=0,293^{\circ}K)} \begin{bmatrix} 1 + \alpha \triangle T \end{bmatrix},$$
 (7)

where α is the thermal expansion coefficient.

The thermal expansion coefficient, α , of 347 stainless steel is given by Corruccini and Gniewek (2, p. 12) and Schwartzberg and coworkers (9, p. B.7.t); Young's modulus as a function of temperature is given by the latter (9, p. B.7.ij). From these references it was determined that:

$$e = f(T) = C_1 + C_2 T + C_3 T^2$$
 (8)

and

$$\beta = f(T) = (C_4 + C_5 \triangle T),$$
 (9)

where C_1 , C_2 , C_3 , C_4 , and C_5 are constants, T is degrees Kelvin, and $\Delta T = T - 293$; the values of the constants are: $C_1 = 1.07418 \times 10^{-5}$, $C_2 = 2.97565 \times 10^{-8}$, $C_3 = -4.230 \times 10^{-11}$, $C_4 = 5.502 \times 10^{-8}$, and $C_5 = 1.97 \times 10^{-11}$.

Therefore,

$$\begin{bmatrix} R_{m} \end{bmatrix}_{(P,T)} = \begin{bmatrix} R_{m} \end{bmatrix}_{(P=0,293^{\circ}K)} \begin{bmatrix} 1 + \alpha \triangle T \end{bmatrix} \begin{bmatrix} 1 + \beta P \end{bmatrix} .$$
(10)

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The merges experience contributent, 2, of 16) stainings areal to given by Corrunated and Ondersk (2, p. 12) and atwartatory and considers (2, p. 4.7.2); frang's modulus as a function of conference to given by the latent (2, p. 5.7.1). From mane colorated as an electronice in given by

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$$(8) = E(T) = (0_0 + u_g \Delta t) .$$
 (8)

where C_{11} , C_{21} , C_{31} , and C_{32} are constants. I is degrees follow, and Al = T - 193: the values of the constants are C_{1} = 1.07418 × 10⁻². C_{2} = 2597865 × 10⁻⁸, C_{3} = 4.210 × 10⁻¹¹, C_{4} = 5.602 × 10⁻⁸, and C_{4} = 1.07 × 10⁻⁴¹.

Thereford,
The capillary length as a function of temperature is:

$$L_{T} = f(T) = [L_{T}] [1 + (C_{1} + C_{2}T + C_{3}T^{2}) \Delta T], (11)$$

where C_1 , C_2 , C_3 , T, and $\triangle T$ are the same as previously defined.

Incorporating the temperature and pressure corrections into equation (1) gives

$$\eta = \left[\frac{\pi \Delta P_{e} \left[R_{m}^{4} \right]}{8 Q_{m} L_{(293^{\circ}K)}} \right]$$

$$\left[1 + (C_{1} + C_{2}T + C_{3}T^{2}) \Delta T \right]^{3}$$

$$\left[1 + (C_{4} + C_{5}\Delta T) P \right]^{4} ,$$

$$(12)$$

as δ was shown to be negligible.

Over the pressure range 28 to 1,000 psia, the calculated change in R_m is less than 10 microinches. Higher internal pressures will significantly affect viscosity calculations. Both L_T and R_m change with temperature by approximately 0.001 percent per degree Kelvin. Because the viscosimeter will be operated over wide ranges of temperature and pressure, both corrections are retained in the final working equation for viscosity, equation (12).

AVERAGE RADIUS AND DENSITY EVALUATION BY DIFFERENT METHODS

Superior Tube Company suggested a value of 0.2833 lb/in³ for the density of the 347 stainless steel tubing, based on mole percent weight-

The capillary longeb as a function of temperature is

$$r = r(r) = [r_1] = [r + (r_1 + (r_2 + c_3 r + c_3 r^2) \Delta r] .$$
(11)

where G. C. G. T. and MT are the anes of proviously defined.

Iccorporating the imaperature and pressure corrections into equation

$$= \left[\frac{m_{1}}{2} \left(\frac{m_{2}}{2} \right) \frac{m_{2}}{2} \frac{2}{2} \frac{2}{$$

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Over the pressure range 28 to 1,000 pais, the coloulated thange in N_n is less than 10 addroinches. Signer (atornal pressures will significently affect viscosicy calculations. Both L₁ and R_n change with temperature by approximately 0.001 percent per degree Kelvin, Secause the viscostmeters will be operated over wide ranges of temperature and pressure, both corrections are retained in the final working equation for

AVERAGE REDITS AND DENSITY EVALUATION.

Superior Tube Company suggested a value of 0.2833 15/1n for the

ing from composition analysis. Specific gravity determinations, using distilled water, by the Pantex facility gave 0.2862 lb/in³ for a randomly-selected, 1-foot section. An average density of 0.2856 lb/in³ was computed from the average SIP R_m and the volumetric method (page 7). The latter density value was taken to be the most accurate.

Values for R_m were computed by the volumetric method using the Superior Tube Company and Pantex densities. Using a gas expansion technique⁵ which is independent of density, R_m values were determined

⁵Further information regarding the gas expansion technique developed at the Helium Research Center is available upon request from the Research Director, Helium Research Center, Bureau of Mines, Amarillo, Texas.

for the 32- and 208-foot long capillary tubes as well as an 85-foot long section. These data are summarized in table 5,

ENTRANCE, KINETIC ENERGY, GAS SLIPPAGE, AND GAS COMPRESSIBILITY EFFECTS

The entrance and kinetic energy effects are discussed together; the effects of gas slippage and gas compressibility are examined similarly. These are applied to the 32-foot (971.704 cm) long capillary in the form of a coil 20 inches in diameter using nitrogen at 300° K and pressure levels of 28 and 1,000 psia. It is assumed, a priori, that entrance, kinetic energy, and gas slippage effects for straight tube capillaries apply to the coil. ing from composition analysis. Specific groute, determinations, which distilled water, by the Pantex facility gave 0.2862 (b) is for a randomly-selected, 1-foot section. At secrets analth of 0.2856 (b) in wis computed from the sverage SIP R, and the volumetric method (page 1). The latter density value was taken to be the molt accurate.

Values for h_n were computed by the volumetric method ustan the Superior labe Company and Penter doministics. Using a gus equerion cechnique² which is independent of density; N_n values were decormined

"Further information regarding the gas repairing technique developed at the Heltum Research Genter is available upon request from the basearch Director, Heltum Resourch Conter, Sureau of Stree, Amerillo, Torae.

For the 32- and 208 font long applifary tubes as well as an 33-100

AND GAS COMPRESSIBILITY SPECTS

The untrance and kinetic energy effects are discussed togother, the effects of gas slippings and gas compressibility are essented that larly. These are applied on the 12-foot (011.704 cm) long topiliary fo the form of a soli 20 incluss is discorter using attrogen at 500 K and pressure levels of 28 and 1,000 gets. It is assumed, a priori, that energicates apply to the cult.

Density,				
<u>lb/in³</u>	Source	Method	$\frac{R_m, in \frac{1}{2}}{2}$	L _T , ft
0.2833	Superior Tube Company	Volumetric	0.014281	19
.2862	Pantex Plant	000 000 000 000 de 0 000 000 000 000 000	.015492	19
	Helium Research Center	Gas expansion	.015334	32
	do	can use our can d O use can can an	。015399	85
	do	сант оны сни оны оны d O (но сня сни) ено (20)	.015130	208
2/ .2856		SIP	.015199	19

TABLE 5. - Average radius and density evaluation by different methods

 <u>1</u>/ Average, not including SIP, equals 0.015127 in; average, gas expansion, equals 0.015287 in; average, all, equals 0.015305 in.
 <u>2</u>/ Computed from SIP and volumetric measurements.

DARIE 5. SUMMERSE RADINE AND PROVIDE OVALUATION DU SITUATION CONTRACTOR

Average, not including SIP, sevels 0.01-12

average, all, equals 0.015105 In.

Computed from SIF and volumeric messications

Entrance and Kinetic Energy Effects

Couette suggested correcting Poiseuille's equation for external resistance for the case of flow streamlines entering a thick-walled capillary from a larger conduit, past a square-cut end; further, Brillouin showed that this could be expressed as a hypothetical addition to the length, L_T . The expression for this extra length is nR_m where n is a constant between 0.8 and 0.9. The work of Couette and Brillouin is detailed by Barr (<u>1</u>, p. 20). Using a value of 0.9 for n and 0.0152017 inch (0.0386 cm) for R_m yields at 300° K and 1,000 psia:

$$L_{T} + nR_{m} = 971.742 \text{ cm}$$
 (13)

A calculated viscosity of 200.06 micropoises changes to 200.05 by correcting for the entrance effect. This change is negligible.

The kinetic energy correction, as shown by Barr (<u>1</u>, p. 15) and Swindells and coworkers (<u>10</u>, p. 2), results from acceleration of the streamlines after entering the constricted capillary and is included in the measured pressure drop, ΔP_{me} . If the assumptions are made that steady-state laminar volumetric flow exists at the entrance and that the same kinetic energy is retained throughout the capillary (that is, Q_m is constant), then:

$$\Delta P_{\rm me} = \Delta P_{\rm e} + \Delta P_{\rm Ke} , \qquad (14)$$

where $\triangle P_e$ is the pressure drop used to overcome viscous resistance and $\triangle P_K^{}$ is the pressure drop due to kinetic energy. By way of Barr (<u>1</u>, p. 17), it can be shown that:

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Counties magneted correction foisentille's counties for external restatements for the case of flow strangtings entering a thirt-weiled capillary from a sarger conduit, part a square not end; forther, Brilloarn throad itse only could be expressed as a hepothetical statement to the length, by the secretarion for this extern length is of, could a is a constant buretor of and 0.9. The weight of coulds and follows is detailed to ber (1.9. 10). Using a value of 0.9 for to and 0.61 for face (0.0185 co) for 8 stated at 100 % and 1,000 parts

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A catcularie vincostey or 200.00 micropolees chanada to 200.05 be correcting for the entretice effect. This chonge is additional the kinetic entries correction, as micro by Barn (1, p. 15) and buindells and constitutes (10, p. 1), results from acculeration of the effect measures the constituted capillory and he trained in the measured presence area (2, if the measuretione end the streamlines after measure the constitution end the trained in the measured presence area (2, if the measuretione end the streamlines after measure the constitution of the streamlines (1, the measure of the stream of the streamline end the stream of the stream of the streamline with the stream of the stream of the stream of the streamle is the stream of the

(2))

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where de its the pressure drop det to overclose via out rouldtance and

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$$\Delta P_{e} = \Delta P_{me} - \frac{m\rho Q_{m}^{2}}{\pi^{2} R_{m}^{4}}, \qquad (15)$$

where m is a characteristic physical constant nearly equal to unity and ρ is the density of the flowing fluid. The kinetic energy correction for short capillaries at high volumetric flow rates is significant.

At 1,000 psia and 300° K, the density of nitrogen was interpolated to be 0.07428 g/cm³ from Flynn (<u>3</u>, p. 123). Average experimental values for Q_m and ΔP_{me} were 0.02222 cm³/sec and 0.0678 psi, respectively. For these conditions R_m equals 0.0152017 inch or 0.038612 cm. Substituting into equation (15) gives, for the last term, a value of 1.67 dynes/cm² or about 2.4 x 10⁻⁵ psi which is negligible compared to ΔP_{me} . A viscosity of 200 micropoises would change by 0.05 micropoise by making the correction.

Gas Slippage and Gas Compressibility Effects

By kinetic theory considerations it can be deduced that, in the immediate vicinity of the capillary wall, a layer of gas thinner than the mean free path, λ , of the molecules has a finite velocity (slip) in the direction of flow. It can be shown by way of Klinkenberg (<u>6</u>, p. 4) that the modified Poiseuille equation, corrected for gas slippage, is

$$\eta = \left[\frac{\pi R_{\rm m}^{\rm A} \Delta P_{\rm e}}{8L_{\rm T} Q_{\rm m}} \left(1 + \frac{4c\lambda}{R_{\rm m}} \right) \right]_{\rm (T,P)}, \qquad (16)$$

where a fa a characteristic physical constant nearly equal to unity and p is the density of the floaten-fluid. The kinetic anergy correction for short capillaries at high uniquerate flow cates is significant.

At 1,000 pais and 100° E, the density of nitrogen and internalized to be 0.07025 g/cm² from Fiyma (1, p. 123), Average experimental values for Q₀ and M_{ma} were 0.02222 cm²/see and 0.0078 pet, respectively. For these conditions R₀ equals 0.0157007 inch or 0.036612 cm. Shnaitturing into equation (15) gives, for the last torm, a value of 1.67 dynes/tm² or about 2.4 x 10⁻⁵ pet which is negligible compared to M_{ma} a viscosity of 200 nicrogatises would charge by 0.05 micropoles by making the correction.

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By binetic theory commiterations it can be deduced that, in the immediate vicinity of the equilary walf, a layer of gas thinner than the mean free path, 1, of the molecules has a finite volocity (elip) to the direction of flow. It can be shown by may of filmienberg (6, P. 4) that the modified coloneuille equation, corrected for gas slippage. 10

where c is a numerical constant nearly equal to unity. According to Guevara and Wageman (5, p. 19), this constant has been calculated to be 1.147. A reasonable estimate of the effect of slippage, the term in parentheses, needs to be made at the lowest pressure level, 28 psia, because slippage is more significant at low pressures (and temperatures).

From Flynn (3, pp. 123, 127), extrapolated density and viscosity values for nitrogen at 28 psia and 298° K were 2.33 x 10^{-3} g/cm³ and 178 micropoises, respectively. The mean free path was computed to be 488 x 10^{-8} cm from simple kinetic theory considerations; λ equals $3\eta/\rho c$, where c is the average molecular speed. The value of $4\lambda/R_m$ at 298° K, assumed to apply at 300° K, was evaluated to be 506 x 10^{-6} cm. The value of the slippage term is 1.000506, corresponding to a viscosity correction of 0.1 micropoise.

The differential equation for isothermal steady-state laminar flow of compressible fluids, neglecting slippage, is:

$$Q_{\rm m} \int_{0}^{\rm L} dL = -\frac{\pi R^4}{8\eta} \int_{\rm P_1}^{\rm P_2} \left[\left(\frac{Z_{\rm m}}{Z}\right) \left(\frac{P}{P_{\rm m}}\right) \right] dP , \qquad (17)$$

where Z_m is the compressibility factor for the fluid at the mean system pressure, $P_m = (P_1 + P_2)/2$, and Q_m is the volumetric flow rate at P_m .

For nitrogen, the change in Z from the entrance of the capillary (P_1) to the exit (P_2) is approximately 1 x 10^{-5} at 300° K. The pressure drop across the 32-foot long capillary, at 28 and 1,000 psia, was less

where the a membrical countant matrix equal to wheel advanting to Suevers and Magaman (5, v. 19), this constant has been exculated to be 1.157. A researable contracts of the direct of allphage, the tota he perconneces, needs to be ande at the four (pressure level is follofin-able alignificant at the four (pressure level is follo-

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Minor From 12, no. 121, 1171, antropontate what ty and vincation values for mitrogen at 28 pairs and 298' 4 area 1,31 + 10⁻¹ and 103 x adcropotess, respectively. En mem free path we consider to be 438 x 10⁻² on trow stepto klowite theory considers tons: ' consist Whee 438 x is as trow stepto klowite theory considers tons: ' consist Whee 438 x is apply at 100° K, was evaluated to be 200 x 10⁻² on The value of the sitpests term is 1.000506, corresponding to a viscoalty correction of 0.1 alcremetas.

The differential equation for (arthornel stands outs lastoir flow

where t_{ij} is the compressibility races for the circ flue of a the same restore pressure, $P_{ij} = (P_1 + P_2)/2$, and Q_j is the value and p_j is the value and h = 0.

For altrogen, the shades (5.2 from the concepts of the capiblary (P_{1}) to the suit (P_{1}) is approximately 1 a 10⁻⁵ at 200° K. The presence drop the presence drop serves the 32-foot roop capiblery, at 25 and 1,00° pate, was issue

than one psi. The ratio Z_m/Z , then, is so close to unity that it can be removed from the integral and the compressible gas treated as incompressible as long as this condition obtains.

SUMMARY

Special methods have been developed for measuring physical dimensions of small diameter tubing, and for evaluating the parameters associated with Poiseuille-type viscometry which are inherently dependent on those dimensions. As far as the authors are aware, this study represents the first time that a long section of stainless steel capillary tubing has been comprehensively examined by metrological methods for use in an absolute gas viscosimeter. As the capillary mean radius is considered accurate to 10 millionths of an inch, viscosities can be determined to one micropoise or better. An accurate appraisal of the non-uniformity of the capillary bore, or variations of radius along the length, is made. Although the individual radii are slightly skewed from a normal distribution, the deviations are actual variations in radii rather than a lack of measurement precision. The internal surface finish of the tubing will not measurably affect the viscosity determinations.

The effects of pressure and temperature on the mean radius and overall length are incorporated into a final working equation for viscosity. Corrections for bore non-uniformity, entrance effects, kinetic energy effects, and gas slippage, all implied to be negligible for the tubing used at low volumetric flow rates, can be included in the final working equation for greater accuracy. The capillary internal diameter measurethan and part. The rotte 2, is, then, is so close to only one trees to can be which the second of the rotter and the superset bir yet reached as interpreters that and the superset bir yet reached as interpreters.

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Amount of shall distance that an developed for second to physical shall atom of shall distance that a, and for evaluation the constraints arentated with Poisseufile type characters which are harbonichy dependent on these dimensions. As for an one mathematics are many, this static represents the first time that a tong encirem of transform start sufficient rabing that Press comprehensively seconds of a matril pical methods for vers to an absolute gas visconization is an interpreting that methods for vers to an accurate to 10 millionshold a second of rest wave and the second and accurate to 10 millionshold a second of rest wave and the barrier of the absolute gas visconization of rest and the second of the second accurate to 10 millionshold is a tone, wis continue as the formula to accurate to 10 millionshold is a tone, wis contined as the second accurate to 10 millionshold as a test, vis contines and the length, in manthe ceptifiers here, at vertations of refits along the length, in manthe ceptifiers here, at vertations of refits along the length, in mantion, the deviations are vertael vertaeles that a soluted to the contained and accurate the restriction are vertael vertaeles the state of the testing will accurate the state of the state of the state of the testing will be accurated in a state of the state of the state of the testing will be accurated in a state of the state of the state of the testing will be accurated in a state of the state of the testing will be accurated in a state of the state of the testing will be accurated in the testing of the state of the testing will be accurated in the test of the state of the testing will be accurated in the test of the testing will be accurated in the state of the testing will be accurated in the test of the testing will be accurated in the test of the test of the test of the state of the test of the state of the test of the test of the state of the test of the test of the test of the test of the

The efforts of proceese and ungervature on the must tailine and over all length are incorporated into 3 (100) working equation for viscosity. Corrections for born non-definity, ercance effects, time to anothy effects, and gas allupage, all implied to be ungligible for the tehing used at low volumeters flow rates, can be lociwied in the final working equation for erester accuracy. The capillary internal dismost measurement and its accuracy, however, are the most significant physical parameters in capillary tube viscometry. Because of the very small pressure drops across the system, the gas is treated as an incompressible fluid.

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