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Nonisothermal Velocity Profiles

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Analytical extensions of the Graetz problem to include the effect of varying viscosity have been made by Cherry (*1*), Yamagata (*4*), and Yang (*5*). The corresponding problem which includes the variation of density for the case of the horizontal tube has so far not been solved analytically.

At present there is no experimental information available on measured velocity profiles for flow through horizontal tubes in which the variation of both density and viscosity is important.

The purpose of the present work was to obtain experimental data on velocity profiles for the flow of mineral oil through a horizontal steam heated tube for Reynolds numbers in the laminar range.

EXPERIMENTAL APPARATUS

The apparatus consisted of a centrifugal pump, venturi meter, air cooling coil, calming chamber, inlet section, test section with steam jacket, probe, cooling coil, and discharge tank. A flow diagram of the apparatus is given in Figure 1.

From the venturi exit the oil entered a finned air-cooled coil which was used to lower the temperature of the oil.

The calming chamber was cylindrical and approximately 6 in. in diameter and 6 ft. long. Several screens were placed in the calming section to help damp out any irregular motions in the oil before it entered the inlet section. The temperature of the oil in the calming section was measured with a copper-constantan thermocouple.

The inlet section and test section were smooth, hard-drawn copper tubing 1.055 in. I.D. and had a wall thickness of approximately 0.010 in. The inlet section was joined to the calming section by means of an 0 ring seal and protruded inside the calming section for a short distance. The inlet section was approximately 10 ft. long and was covered with magnesia insulation. The inlet section and test section were joined with a bakelite connector and 0 ring seals in order to keep the metal inlet and test section tubes from touching each other and thus to simulate a step change in wall temperature at the test section inlet. The test section itself was 10.05 ft. long.

The steam jacket was a 3-in. standard pipe which enclosed the test section and was supplied with low pressure wet steam. The steam temperature was measured with a copper-constantan thermocouple.

A depth gauge micrometer with ± 0.001-in. divisions was used to position the probe. The probe was a total pressure probe and was made of 0.072 in. O.D. hypodermic tubing with a tube wall thickness of 0.0090 in. The static pressure was obtained from a small hole in the test section wall. The difference between the total and the static pressure was read by means of an inverted U-tube manometer with air in the top portion of the manometer. In this way mineral oil at room temperature was used to indicate the difference between the total and static pressure.

Following the probe was a short section of copper tubing connecting the exit of the probe housing with the discharge tank. A coil of copper tubing with water flowing through it was used to cool the oil as it passed through the discharge tank.

From the discharge tank the oil returned to the pump. The discharge tank was located above the pump so that there was always a positive head on the pump.

RESULTS AND DISCUSSION

Tests were run under isothermal conditions to determine the velocity profiles at inlet to the test section. These tests indicated that the inlet profiles were within ± 5% of the corresponding parabolic ones. Runs were made at Reynolds numbers of 650, 950, and 1,325. A maximum value of r/r_o of 0.57 was used in these tests.

Five heated runs were made, and five vertical and three horizontal velocity profiles were taken at the test section exit. The Reynolds number in the test section, based on the inside tube diameter, varied from 850 to 1,400. The corresponding Graetz, Prandtl, and Grashof numbers as well as μ_b/μ_w were essentially the same for all runs. As a consequence the vertical and horizontal velocity profiles were essentially the same for all runs made.

The tube Reynolds number, Prandtl number, Grashof number, and Graetz number were calculated with properties evaluated at the average bulk temperature. The Grashof number was based on tube inside diameter and arithmetic mean temperature difference. The outlet bulk temperature was not measured but was estimated by an energy balance. The specific gravity of the oil used in these experiments and hence the density and the value of β were obtained with a hydrometer. The kinematic viscosity was obtained with a viscometer, and the thermal conductivity was measured in a parallel plate apparatus. The specific heat was not measured but was estimated from data on similar oils. A summary of the property values used is given in Table 1.

As is well known (*2, 5*) at low probe Reynolds number the pressure coefficient for a square-edged total pressure probe of the type used in these experiments is unity for values of the probe Reynolds number greater than 20, where the probe Reynolds number is based on the outside probe

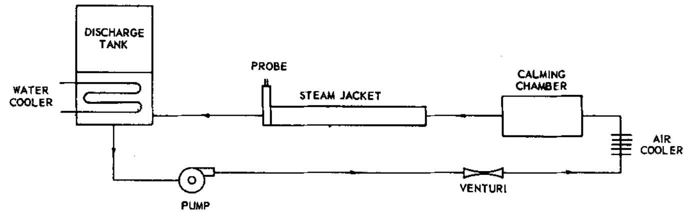

Fig. 1. Schematic of apparatus

(*Continued from page 140*)

INFORMATION RETRIEVAL

Key Words: Gas-Metal Permeation-8, 7, Permeation-8, 7, Hydrogen-1, Diffusion-8, Stainless Steel-1, Permeability-8, 7, Interfacial Resistance-8, Richardson Equation-8, Inverse Thickness-6, Diffusivity-8, Variable Thickness-6, Computer-10.
Abstract: The permeation rate of hydrogen through cylindrical membranes of type 321 stainless steel was found to deviate from the square-root-of-pressure and inverse-thickness relations predicted by the Richardson equation. Slow surface reactions, coupled with diffusion, are considered to be the cause of the observed deviations. The permeation data are correlated by a semiempirical interfacial resistance model.

Permeation rates were observed to change with time of membrane exposure to hydrogen. It is believed this resulted from changing surface activity.

Permeation rates were computed by a least-squares technique programmed for the IBM-650 data processing system.
Reference: Phillips, J. R., and B. F. Dodge, **A.I.Ch.E. Journal, 9,** No. 1, p. 93 (January, 1963).

Key Words: Flow-8, Fluid Flow-8, Fluid Mechanics-8, Fluids-8, Non-Newtonian-, Pseudoplastic-, Channels-9, Conduits-9, Pressure Drop-9, Profiles-9, Velocity-9, Theories-10, Boundary-Layer-, Computers-10.
Abstract: Boundary-layer theory has been applied to two dimensional flow of non-Newtonian fluids in the entry region of a channel. The analysis considers pseudoplastic fluids which can be described by a power-law relationship between shear stress and velocity gradient. Results include estimates of entry length, pressure loss, and velocity profiles for such fluids.
Reference: Collins, Morton, and W. R. Schowalter, **A.I.Ch.E. Journal, 9,** No. 1, p. 98 (January, 1963).

Key Words: Fluid Flow-8, Flow-8, Mixed-Phase- , Mass Transfer-8, Diffusion-9, Distribution-9, Holdup-9, Porosity-9, Packings-9, Eddy Diffusivity-9, Concentration-9, Shape Factors-9, Liquids-1, Gases-1, Fluids-1, Tracers-1, Pores-5, Channels-5, Voids-5, Flow Rates-6, Velocities-6, Residence-7, Dispersion-7, Beds-10, Packed- , Models-10, Moments-10.
Abstract: Mixed phase flow in a packed bed of porous particles consists of channel and diffusional flow outside the particles through continuous void channels. Inside the particles, flow is in contiguous pore channels and dead-ended pockets. Mathematical treatment of this physical model is valid for the case of laminar flow and relates the mean liquid residence time and a reciprocal Peclet number dispersion parameter to measurable flow and bed parameters. The model predicts that the dispersion parameter should increase linearly with liquid velocity which is verified with experimental data from operations at low space velocity.
Reference: Glaser, M. B., and Mitchell Litt, **A.I.Ch.E. Journal, 9,** No. 1, p. 103 (January, 1963).

Key Words: Chromatography-1, Partition-1, Column-5, Perturbation-10, Velocity-7, Separation-2, Mathematical-10, Analytic-10, Numerical-10, Characteristics-10, Partition (Coefficients)-2, Residence (Time)-2, Dilution-6, Tracers-4.
Abstract: The equations are set up for the flow of a multicomponent gas mixture through a bed of porous solid supporting a fixed liquid phase. With assumptions likely to be valid in gas liquid partition chromatography these equations are solved analytically for the characteristic velocities associated with a small perturbation of an arbitrary equilibrium condition of the system.
Reference: Stalkup, Fred I., and H. A. Deans, **A. I.Ch.E. Journal, 9,** No. 1, p. 106 (January, 1963).

Key Words: Drops-10, Supported- , Hypodermic Tubing-10, Wind Tunnel-10, Oscillation-6, Mass Transfer-9, Sulfur Dioxide-5, Glycerine-5, Propylene Glycol-5, Ethylene Glycol-5, Diffusivity-7, Effective- , Frequency-7, Amplitude-7, Velocities-7, Circulation-7, Cinematography-10, Sublimation-8, Coefficients-7, External- , Naphthalene-5, Air-5, Spheres-10, Physical Properties-8, Properties (Characteristic)-8.
Abstract: Single drops supported on hypodermic tubing were studied in a wind tunnel to determine the effect of drop oscillation on mass transfer. The systems studied were sulfur dioxide gas and drops of glycerine, propylene glycol, and ethylene glycol. The results are expressed in terms of effective diffusivity. Frequencies, amplitudes, and internal circulation velocities were studied by cinematography. The effect of oscillation on external mass transfer coefficients was studied by sublimation of naphthalene spheres in air. A technique has been developed for studying the effect of internal circulation of effective diffusivity, with forced circulation through a drop suspended on hypodermic tubing.
Reference: Constan, G. L., and Seymour Calvert, **A.I.Ch.E. Journal, 9,** No. 1, p. 109 (January, 1963).

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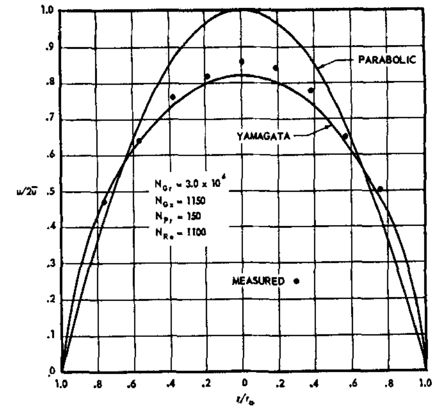

Fig. 2. Horizontal profile.

radius and the local velocity. This result was confirmed with data taken at the center line of the tube. Preliminary calculations indicated that all of the probe Reynolds numbers would probably be greater than 30 for all of the data intended to be taken. Thus in calculating the velocity profiles it was initially assumed at each point that the probe pressure coefficient was unity. Then the probe Reynolds number was calculated in order to confirm this assumption. In all of the data presented here this condition was satisfied.

Figure 2 is a typical horizontal velocity profile, and Figure 3 is a typical vertical velocity profile. Both figures include a parabolic profile and a profile calculated by the method of Yamagata (*4*) for comparison. In both cases the wall temperature was 212°F. and the inlet oil temperature was 118°F.

As indicated by Figure 2 the horizontal velocity profiles, as anticipated, are essentially symmetric. Also as anticipated none of the vertical profiles were symmetrical. They all exhibited a maximum velocity below the center line of the tube due to the free convection effects.

An estimate of the experimental error introduced by errors in the venturi and probe manometers indicated a maximum error of ± 5% in $u/2\bar{u}$.

ACKNOWLEDGMENT

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TABLE 1. PROPERTIES OF OIL

Temperature, °F.	Specific gravity	$\beta \times 10^4$	$\nu \times 10^4$	k	C_p
100	0.842	3.86	2.36	0.093	0.46
140	0.829	3.92	1.18	0.092	0.48
180	0.816	3.98	0.70	0.092	0.50
220	0.803*	4.05	0.45	0.091	0.51

* Extrapolated from 200°F.

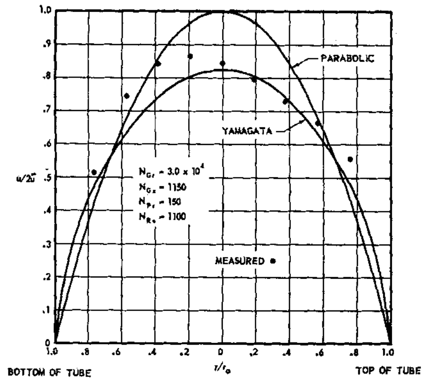

Fig. 3. Vertical profile.

NOTATION

c_p = specific heat at constant pressure, B.t.u./(lb.) (°F.)
D = inside diameter of test section, ft.
g = acceleration of gravity, (ft./sec.)/sec.
k = thermal conductivity, B.t.u./(hr.) (sq. ft.) (°F./ft.)
L = length of test section, ft.
N_{Gr} = Grashof number, $D^3\beta g(t_w - t_b)/\nu^2$
N_{Gz} = Graetz number, $c_p L\rho\bar{u}/k$
N_{Pr} = Prandtl number, $\mu c_p/k$
N_{Re} = Reynolds number, $D\bar{u}/\nu$
r = radial coordinate, ft.
r_o = inside radius of test section, ft.
t_b = average bulk temperature, °F.
t_w = tube wall temperature, °F.
u = local velocity parallel to tube axis, ft./sec.
$\bar{u}$ = mass average velocity in tube, ft./sec.

Greek Letters

β = volumetric coefficient of expansion, (cu. ft./cu. ft.)/°F.
ρ = density, lb./cu. ft.
μ = absolute viscosity, lb./(sec.) (ft.)
μ_b = absolute viscosity evaluated at bulk temperature, lb./(sec.) (ft.)
μ_w = absolute viscosity evaluated at wall temperature, lb./(sec.) (ft.)
ν = kinematic viscosity, sq. ft./sec.

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Abstracts

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