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FORCED-CONVECTION HEAT-TRANSFER CORRELATIONS FOR GASES FLOWING THROUGH WIRE MATRICES AT SURFACE TEMPERATURES TO 5500° R

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Lewis Research Center
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SUMMARY

Experimental forced-convection heat-transfer data are presented for hydrogen, helium, and nitrogen gases flowing through electrically heated matrices made of helical coils of tungsten wire. The following are the test conditions for these data: wire diameter, 0.030 to 0.050 inch; surface temperature, 1500° to 5500° R; outlet gas temperature, 650° to 3000° R; mass velocity, 0.34 to 7.01 pounds per second per square foot; heat flux, 0.32 to 8.43 Btu per second per square inch; pressure, 1 atmosphere; porosity, 60 to 80 percent. The data are correlated by using the wire diameter as the characteristic dimension, basing the Reynolds number on the minimum mass velocity, and evaluating the physical properties of the gases at both the film and bulk temperatures. These data and those of other investigators can be represented by the single-cylinder heat-transfer correlation based on the film temperature or by a bulk-temperature correlation presented herein. Matrix types include coils, cylinder banks, and woven wire screens having porosities greater than 60 percent.

INTRODUCTION

The Lewis Research Center is investigating the use of nuclear fuel elements in space power and propulsion systems. For reasons of safety and economy the initial testing of these elements at simulated operating conditions is being done out-of-pile. Many of these tests require a steady-state source of hot flowing gas at temperatures up to 5000° R. The development of electrical-resistance heaters for hot-flow testing resulted in an investigation of the heat-transfer characteristics of tungsten-wire-matrix heating elements. Tungsten wire can be electrically heated to surface temperatures above 5000° R, and, as a matrix, it has a high surface-to-volume ratio and is adaptable to either high-voltage or high-current power supplies.

There is no universal forced-convection heat-transfer correlation that encompasses the wide range of heat-transfer surface geometries that can be formed from wire. The available data listed in the literature indicate that each type of wire matrix exhibits slightly different heat-transfer characteristics. Reference 1 summarizes experimental data obtained for air flowing through woven matrices of different wire diameters and porosities at temperatures slightly above ambient. Reference 2 provides some variable-property data for the steady-state flow of air through electrically heated banks of cylinders at surface temperatures up to 1100° R. Reference 3 presents variable-property data for hydrogen and nitrogen gases flowing through interwound helical coils of tungsten wire heated electrically to surface temperatures up to 5200° R. In each of these reports a particular correlation was obtained for each type of matrix investigated.

The lack of geometrical similarity is the primary reason why each matrix behaves somewhat differently. However, if this geometry difference is not great, a single correlation might represent all the matrices. This report presents variable-property heat-transfer data for one geometry and relates these data and those of other investigators of similar geometries to one general correlation.

The data presented are for hydrogen, helium, and nitrogen gases flowing through a matrix formed from helical coils of tungsten wire. The arrangement of coils differed from that of reference 3 in that the coils were not interwound. The wire diameter varied from 0.030 to 0.050 inch, and the porosity varied from 60 to 80 percent. The heat flux ranged from 0.32 to 8.43 Btu per second per square inch. The experimental data are correlated by using the wire diameter as the characteristic dimension, basing the Reynolds number on the minimum mass velocity, and evaluating the physical properties of the gases at both the film and bulk temperatures. The data of references 1 to 3 are correlated herein on these same bases.

APPARATUS AND PROCEDURE

A schematic diagram of the flow system, test section, power supply, and instrumentation and of corresponding components associated with each as used in the investigation is shown in figure 1.

Flow System

As may be seen in figure 1, hydrogen, nitrogen, or helium was supplied to the flow system from a tube trailer at a maximum pressure of 2400 pounds per square inch. From the trailer the gas flowed through a preset pressure-reducer valve, a remotely operated control valve, a convergent-divergent flow nozzle, and an on-off valve before it entered the test section. The gas flow was metered by means of the flow nozzle, which was maintained choked to ensure a constant mass flow through the test section. From the test section the heated gas flowed through a two-baffle molybdenum mixing can and into a gas-to-water concentric-tube heat exchanger, where it was cooled below 1000° R before it was exhausted into the atmosphere.

For safety purposes, the entire system was purged with nitrogen before hydrogen flow was started, and the controls were set for fail-safe operation; if a predetermined safety permissive stopped the hydrogen flow, nitrogen would automatically purge the system. In such a case, the electrical test power would also be automatically shut down.

Test Section

Operating experience with heating elements made from the interwound coils of reference 3 showed that this type of matrix, when heated electrically, was susceptible to hot spotting and subsequent burnout at high heat fluxes. Tests showed that nonuniformities in the interwound geometry resulted in flow maldistribution within the matrix. A search for a similar but less flow-restrictive heating element led to a matrix made of noninterwound coils. In figure 2 this noninterwound matrix is compared to the interwound matrix of reference 3.

Heat-transfer experiments were performed on this type of matrix formed by helical coils of tungsten wire positioned side by side with minimum spacing between coils. The various parameters are listed in table I. Both single and double rows of coils in the direction of flow were tested. The coils ended in a straight portion of wire which was sandwiched between two 0.060-inch-thick tungsten plates to form buses. The coil ends were heliarc welded to the plates to provide positive mechanical and electrical connections. A 1/8-inch segment of the straight wire remained exposed on each end of the coil between the tungsten plates and the beginning of the helix.

Figure 3 shows an exploded view of the test section assembly. The entering flow was straightened by a 3-foot entrance-transition section. The gas then passed through the matrix, which was held in place by a boron nitride housing. The housing also served to insulate the bus connections of the matrix. A rubber O-ring near the cold end of the boron nitride eliminated bypassing of the gas. The gas was mixed by a molybdenum baffle before its temperature was measured. The outer stainless-steel support housing was water cooled.

Power Supply

A single-phase 60-cycle 500-kilovolt-ampere saturable-reactor-controlled power supply was used to heat the tungsten matrix electrically. Output voltage was varied from 6.0 to 55.8 volts with a maximum current rating of 10 000 amperes. With bus losses, however, the maximum power to the test element was limited to 225 kilowatts.

Instrumentation

The location of the instrumentation is shown in figure 1. The voltage across and the current through the test section were measured. The test-section voltage was taken directly across the matrix to eliminate any error caused by a voltage drop between the power supply and the test section. A true root-mean-square voltmeter was used to measure the test voltage because of the nonsinusoidal waveform produced by the saturable-reactor-controlled power supply. Current was read on a precision alternating-current ammeter through a 4000:1 step-down current transformer. Inlet temperature was measured with a type-K thermocouple (ref. 4), and the exit temperature was measured with a platinum - platinum-13-percent-rhodium thermocouple. The exit thermocouple was placed in a baffled molybdenum mixing can to give a true mixed bulk-gas temperature. Temperature and pressure measurements at the inlet to the choked flow nozzle were made to calculate mass-flow rate. The mass-flow rate was set by adjusting the nozzle-inlet pressure.

METHOD OF CALCULATION

Geometrical Factors

The matrix was made of helical tungsten coils positioned side by side. This matrix can be specified by the following parameters: (1) wire diameter d, (2) mandrel diameter (inside coil diameter) D, (3) number of parallel coils per unit width N, (4) length of coil b, and (5) helical coil pitch p.

The geometrical parameters and corresponding equations associated with the calculation of the heat-transfer coefficient and of the surface temperature for the data of this report are as follows: The length S of wire in a single helical coil, including the total exposed straight segments (0.021 ft) on the coil ends, is given by the equation

$$S = \frac{b}{p}\sqrt{\pi^2(D + d)^2 + p^2} + 0.021 \tag{1}$$

and the total heat-transfer area for N number of coils is

$$A_s = \pi dSN \tag{2}$$

(Symbols are defined in the appendix.)

The mass velocity was defined in two ways. The first, which is the definition used in the correlating equations of this report, gives the minimum mass velocity at a point just upstream of the matrix. It uses the total frontal area of the matrix for the cross-sectional flow area:

$$G_{min} = \frac{W}{A_{ft}} \tag{3a}$$

The second definition is that of the average mass velocity through a porous structure and is based on the average porosity of the matrix:

$$G_{av} = \frac{W}{A_{ft}\epsilon} \tag{3b}$$

The porosity of a homogeneous matrix is usually defined as the ratio of void volume to total volume. However, for a matrix made from noninterwound coils this definition is not realistic because of the large void volume within the center of each coil. The porosity of this system was therefore based on the coil volume minus the center or mandrel volume. Equation (4) defines this porosity in terms of one coil which is applicable to the total matrix when the coils are positioned close together:

$$\epsilon = \frac{(\text{volume of coil} - \text{volume of mandrel}) - (\text{volume of tungsten in coil})}{\text{volume of coil} - \text{volume of mandrel}} \tag{4}$$

This porosity, when multiplied by the frontal area of the matrix, approximates the average flow area between turns in the coils.

Average Heat-Transfer Coefficients

The average heat-transfer coefficient was computed from the experimental data by the relation

$$h = \frac{Q}{A_s(T_s - T_b)} = \frac{Wc_{p,b}(T_2 - T_1)}{A_s(T_s - T_b)} \tag{5}$$

where

$$T_b = \frac{T_1 + T_2}{2} \tag{6}$$

The average surface temperature T_s of the matrix was determined from the relation between temperature and resistivity of tungsten as given in reference 5. The resistivity was calculated from

$$\xi = \frac{V}{I}\frac{A_e}{S} \tag{7}$$

where

$$A_e = \frac{\pi N d^2}{4} \tag{8}$$

Average surface temperatures from the resistivity-temperature relation calculated by equation (7) were verified by means of an optical pyrometer that was sighted through a port located in the inlet-transition section of the test-section housing.

The film temperature used to evaluate the physical properties of the gases is defined by

$$T_f = \frac{T_b + T_s}{2} \tag{9}$$

The physical properties for hydrogen were taken from reference 6 and those for helium and nitrogen from reference 7.

RESULTS AND DISCUSSION

A fluid flowing normal to a single cylinder is analogous to a fluid flowing normal to a wire matrix such as those shown in figure 2. In each case a laminar boundary layer forms on the upstream portion of the surface, and flow separation generally occurs at some point on the downstream portion of the surface. A similar analogy can be made for the transfer of heat from both a cylinder and a matrix to a flowing fluid. On the front portion of the surface the heat is transferred through the laminar boundary layer that has developed. On the back portion the heat is transferred by the turbulent action of the wake that forms with flow separation. The mechanism of heat transfer from such surfaces cannot be analytically defined at the present time. The factors that determine the heat-transfer coefficient for fluids flowing normal to cylinders are the same factors that define any forced-convection heat transfer; these are the mass velocity of the fluid, the physical properties of the fluid at some reference temperature, and the characteristic dimension of the system, which in this case is the cylinder diameter. For a single cylinder the mass velocity is based on the total cross-sectional area of the flow passage. As more cylinders are added, a matrix is approximated, and the mass velocity of the fluid through the matrix increases as the porosity of the system decreases. However, the average porosity does not necessarily define the effective mass velocity because it does not describe the variable cross-sectional areas available for flow. Other factors, such as the action of the turbulent wake from one cylinder on an adjacent or on a downstream cylinder, will also affect the mass velocity. This complex fluid flow through a matrix requires that experimental data be used to define such a system empirically. The definition of mass velocity used will be that which yields the best correlation. For this investigation the minimum mass velocity based on the frontal area of the matrix gave the best results.

Reference 8 recommends the following empirical equation for determining the heat-transfer coefficient of air flowing normal to a single cylinder:

$$Nu_f = 0.32 + 0.43\, Re_f^{0.52} \tag{10}$$

This equation applies for the following ranges of variables:

Cylinder diameter, d, in.	0.0004 to 5.9
Surface temperature, T_s, ^{o}R	530 to 2300
Outlet gas temperature, T_2, ^{o}R	520 to 960
Film Reynolds number, Re_f	0.1 to 1000
Porosity, ϵ, percent	$\approx$100

Equation (10) was modified to include the effect of Prandtl number ($Pr_f = 0.74$ for air) as in the modification presented in reference 8. The following equation represents the heat transferred to any gas flowing normal to single cylinders:

$$\frac{Nu_f}{Pr_f^{0.4}} = 0.36 + 0.48\, Re_f^{0.52} \tag{11}$$

This equation was used as a reference to compare the experimental data of this report for noninterwound, helically coiled, wire matrices and the data of other investigators for different types of wire matrices.

The experimental data of this investigation are presented in table II. The conditions for these data were as follows:

Wire diameter, d, in.	0.030 to 0.050
Surface temperature, T_s, ^oR	1500 to 5500
Outlet gas temperature, T_2, ^oR	600 to 3000
Heat flux, Q/A_s, (Btu/sec)/in.^{2}	0.32 to 8.43
Film Reynolds number, Re_f	51 to 1250
Porosity, ϵ, percent	60 to 80

The data were correlated by using the wire diameter as the characteristic dimension, basing the Reynolds number on the minimum mass velocity, and evaluating the physical properties of the gases at the film temperature. Hydrogen, nitrogen, and helium gases were used because these were the fluids to be used in the fuel element testing program. Figure 4 shows these data and compares them with the single-cylinder data represented by equation (11). The multicoil data of this investigation fall within +10 percent and -20 percent of equation (11).

The fact that the single cylinder correlation represents the data for heat-transfer surfaces made of coils is significant, and further substantiation of this may be seen in figures 5 to 7, in which the data of other investigators are correlated on the same basis as those in figure 4.

Figure 5 shows the data of reference 3 for interwound helical coils of tungsten wire such as those shown in figure 2(b). These data were obtained with hydrogen and nitrogen gases for the following ranges of conditions:

Wire diameter, d, in.	0.020 to 0.035
Surface temperature, T_s, ^{o}R	1400 to 5200
Outlet gas temperature, T_2, ^{o}R	600 to 2400
Heat flux, Q/A_s, (Btu/sec)/in.^{2}	0.5 to 8.3
Film Reynolds number, Re_f	27 to 800
Porosity, ϵ, percent	64 to 72

The single cylinder equation (11) represents the majority of these data within ±20 percent.

Figure 6 shows the data of reference 2 for air flowing normal through an electrically heated bank of cylinders for the following conditions:

Cylinder diameter, d, in.	0.020
Average surface temperature, T_s, ^{o}R	683 to 1109
Outlet gas temperature, T_2, ^{o}R	598 to 961
Film Reynolds number, Re_f	35 to 770
Number of rows, M	8
Porosity, ϵ, percent	60

The majority of the data parallel the single-cylinder correlation but fall about 25 percent above it. The greater heat transfer for the same mass flow may be explained by the effect of air flow through more than one row of cylinders. Multiple rows of cylinders increase the turbulence of the fluid (ref. 8) and cause greater heat transfer than that obtained for fluids passing over a single cylinder or over one or two rows of coils.

Figure 7 shows the data of reference 1 for air flowing through woven-wire matrices for the following ranges of conditions:

Wire diameter, d, in.	0.0075 to 0.041
Bulk Reynolds number, Re_b	2 to 227
Porosity, ϵ, percent	60 to 83

These data also fall above the single-cylinder correlating line. Since these test elements consisted of from 3 to 65 rows stacked together, the increased turbulence caused by the multiple rows again indicates the reason for the greater heat transfer. These data are based on bulk-temperature physical properties, whereas the data of previous investigators were based on film temperature. This change should not be significant because the actual difference between the surface and bulk temperatures for these data was reported to be only about 30^{o} R (refs. 1 and 9).

The data of this investigation and those of references 1 to 3 were also correlated by using the bulk temperature instead of the film temperature to evaluate the physical properties of the fluids. The results shown in figure 8 indicate a reasonably good correlation.

The correlating line was drawn through the multiple-row data of references 1 and 2. The majority of the single-row data of reference 3 and of this investigation fall below the line, as would be expected because of lower turbulence. The single-row data exhibit more scatter probably because the variable property effect is not represented by a bulk-reference temperature. The following equation represents the single-row data within an accuracy of +24 percent and -32 percent and the multiple-row data within ±15 percent:

$$\frac{Nu_b}{Pr_b^{0.4}} = 0.75\, Re_b^{0.52} \tag{12}$$

The conclusion from this comparison is that both equation (11) (single-cylinder correlation) and equation (12) represent the heat transfer for different types of wire matrices. These types include a single cylinder, multiple cylinders, woven wires, interwound coiled wires, noninterwound coiled wires, and probably any other type of matrix surface that can be described by a cylinder diameter as the characteristic dimension and which has a porosity greater than 60 percent. The comparison also makes it apparent that each type of matrix behaves somewhat differently from the others, and if an accurate heater design is required, it will be necessary to obtain experimental data on the particular matrix being considered.

Prior investigators of matrix heat-transfer surfaces have correlated their data on the basis of an average flow area through which the fluid flows; that is, the mass velocity was based on a frontal area multiplied by the porosity of the matrix. This would seem to be a more reasonable approximation of the flow conditions throughout the matrix than the velocity of the fluid based on the total flow area of the passage. The average flow area was used as the basis for correlating the data of this investigation and those of references 2 and 3. Although these correlations are not presented herein, they showed that the data for each type of matrix correlated within ±20 percent of a mean correlating line, but a general correlation for all of the data was not obtained. This does not mean that porosity is not a significant variable. It suggests that for the range investigated herein (greater than 60 percent) other factors overshadowed the porosity effect, and the definition of porosity used did not accurately represent the flow conditions throughout the matrix. There is certainly some lower porosity limit at which its effect becomes dominant.

SUMMARY OF RESULTS

Heat-transfer data at 1 atmosphere pressure were obtained for forced convection of hydrogen, helium, and nitrogen gases through noninterwound coils of tungsten wire electrically heated to surface temperatures up to 5500° R. Outlet gas temperatures as high as 3000° R were obtained, and film Reynolds numbers based on wire diameter and total-passage flow area varied from 50 to 1250. The results of comparing these data and those of other investigators are as follows:

1. The experimental data for mesh heat-transfer surfaces made from single cylinders, interwoven wires, interwound coils, and noninterwound coils can be represented by the single-cylinder heat-transfer correlation or by the correlation presented herein.

2. The different geometries of the various types of matrices cause each to possess slightly different heat-transfer characteristics. If a high degree of accuracy is required for the design of a matrix heat-transfer system, it will be necessary to obtain experimental data on the particular matrix being considered.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 26, 1967,
120-27-04-56-22.

APPENDIX - SYMBOLS

A_e current-flow cross-sectional area, sq ft

A_{ft} frontal area, sq ft

A_s heat-transfer surface area, sq ft

b length of coil, ft

c_p specific heat of gas at constant pressure, Btu/(lb)($^{\circ}$R)

D mandrel diameter, ft

d wire, or cylinder, diameter, ft

G_{av} average mass velocity within matrix, (lb/sec)/sq ft

G_{min} mass velocity upstream of matrix, (lb/sec)/sq ft

h average heat-transfer coefficient, Btu/(sec)(sq ft)($^{\circ}$R)

I current, A

k thermal conductivity of gas, Btu/(ft)(sec)($^{\circ}$R)

M number of coil rows

N number of parallel coils per unit width

Nu Nusselt number, hd/k

P pressure, psig

Pr Prandtl number, $c_p\mu/k$

ΔP differential pressure, psi

p coil pitch, ft/turn

Q rate of heat transfer to gas, Btu/sec

Re Reynolds number, dG/μ

S total wire length of helical coil, ft

T temperature, $^{\circ}$R

T_b average bulk temperature, $(T_1 + T_2)/2$, $^{\circ}$R

T_s average surface temperature, $^{\circ}$R

T_1 inlet gas temperature, $^{\circ}$R

T_2 outlet gas temperature, $^{\circ}$R

V voltage, V

W gas flow rate, lb/sec

ϵ matrix porosity, percent

μ absolute viscosity of gas, lb/(sec)(ft)

ξ resistivity of tungsten, ohm-ft

Subscripts:

b bulk

f film

s surface

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TABLE I. - MATRIX GEOMETRIC PARAMETERS

[Matrix size and channel flow area, 3 in. long by 1 in. wide.]

Mesh number	Parameter					
	Wire diameter, d, in.	Mandrel diameter, D, in.	Number of parallel coils, N	Number of coil rows, M	Coil pitch, p, in./turn	Porosity, ϵ, percent
1	0.030	0.060	8	1	0.060	59.8
2	.030	.060	9	1	.120	78.7
3	.030	.100	11	2	.060	60.3
4	.040	.060	8	1	.080	59.5
5	.040	.100	11	2	.080	60.1
6	.040	.100	6	1	.160	79.1
7	.040	.100	11	2	.160	79.1
8	.050	.060	6	1	.100	59.3
9	.050	.100	5	1	.100	60.0
10	.050	.100	9	2	.100	60.0
11	.050	.100	5	1	.200	78.7
12	.050	.100	9	2	.200	78.7

TABLE II. - EXPERIMENTAL DATA

Gas	Matrix	Voltage, V	Current, I, A	Average surface temperature, T_s, ^oR	Gas flow rate, W, lb/sec	Inlet gas temperature, T_1, ^oR	Outlet gas temperature, T_2, ^oR
Nitrogen	1	15.9	380	2811	0.0866	535	761
		23.0	404	3636	.0866		866
		13.7	384	2485	.1070		695
		22.0	416	3422	.1070		805
	5	15.9	660	3315	0.0323	470	1437
		30.6	924	4325	.0791		1483
		18.7	820	3165	.0799		1085
		25.5	960	3585	.1344		1040
		30.0	1000	3960	.1344		1147
	6	6.0	348	2555	0.0460	535	670
	7	7.8	760	2882	0.0665	535	783
	9	7.4	420	2152	0.0665	535	695
		12.3	456	3088	.0665	535	795
		19.0	460	4406	.0665	535	965
	10	11.4	836	2852	0.0665	535	945
		10.6	916	2482	.1070		804
		18.2	1012	3592	.1070		1017
		10.7	1000	2326	.1460		742
		18.8	1076	3505	.1460		936
Helium	1	20.8	640	2274	0.0590	535	729
		28.5	668	2863	.0590	535	815
	2	11.8	736	2324	0.0347	535	714
		17.3	764	3105	.0347		804
		21.0	768	3630	.0347		871
		17.6	804	3019	.0509		761
	6	17.5	660	3661	0.0186	535	964
		11.0	692	2385	.0347		693
		16.5	720	3249	.0347		777
		11.9	744	2394	.0509		670
	7	7.0	1040	1928	0.0186	535	825
		13.0	1120	3050	.0186		1085
		8.8	1220	2038	.0347		750
		12.4	1260	2150	.0347		871
		6.6	1292	1523	.0509		655
		12.9	1376	2549	.0509		804
	8	12.5	1008	2380	0.0347	535	785
		24.0	1048	3975	.0347	535	1021
	9	15.6	880	2165	0.0590	535	696
		20.5	900	2674	.0590	535	775
	10	12.5	1404	1992	0.0347	535	886
		18.0	1460	2618	.0347	535	1058
		21.5	1620	2788	.0509	535	1002
	11	16.1	820	3955	0.0510	535	740
	12	6.8	1272	2174	0.0347	535	721
		6.4	1388	1922	.0509	535	670
		8.8	1425	2458	.0509	535	730
Hydrogen	3	55.8	860	3920	0.0073	490	2149
		55.5	948	3610	.0130		1602
		55.5	1008	3420	.0187		1380
		24.5	936	1835	.0244		785
		34.5	984	2350			925
		44.1	1016	2790			1058
		55.5	1056	3315			1211
		55.5	1104	3190	.0300		1104
		55.5	1148	3085	.0355		1021
	4	14.1	812	2510	0.0070	470	925
		26.4	912	3830	.0070	470	1372
		53.0	1920	5515	.0130	490	3020
		25.1	1100	3155	.0232	470	805
		40.0	1216	4285	.0232		1035
		38.1	1268	3960	.0338		867
		48.8	1348	4650	.0338		1000

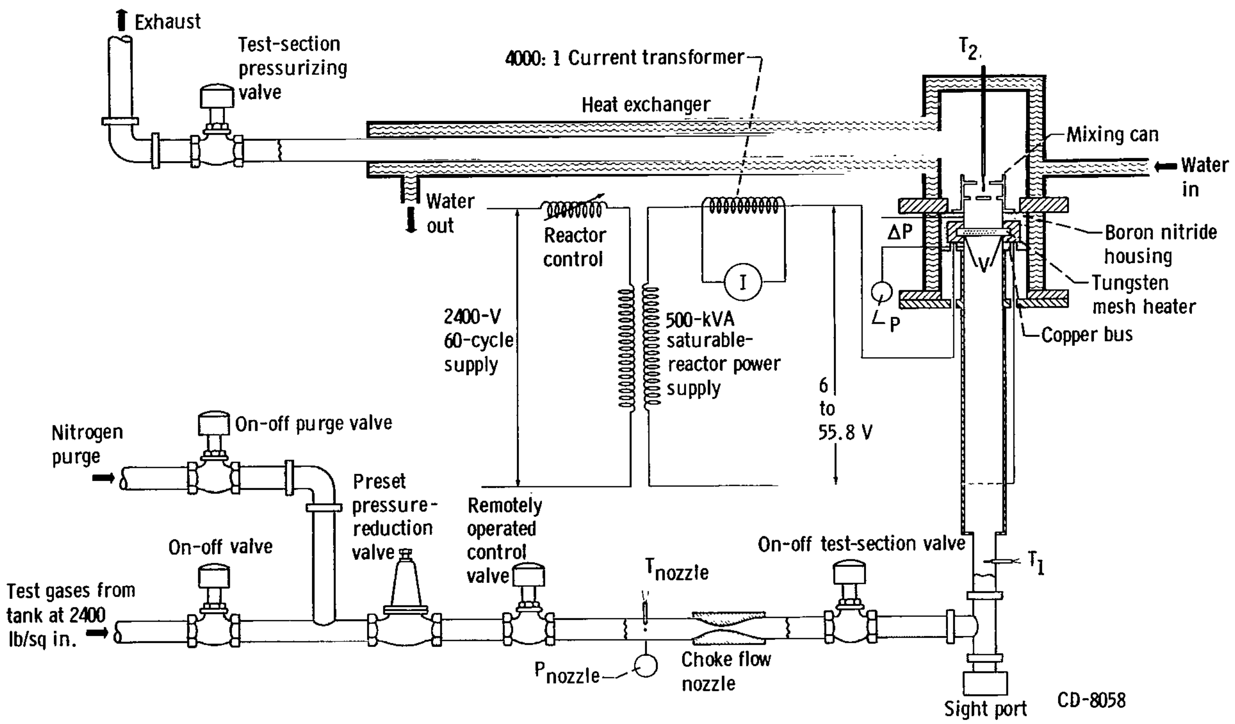
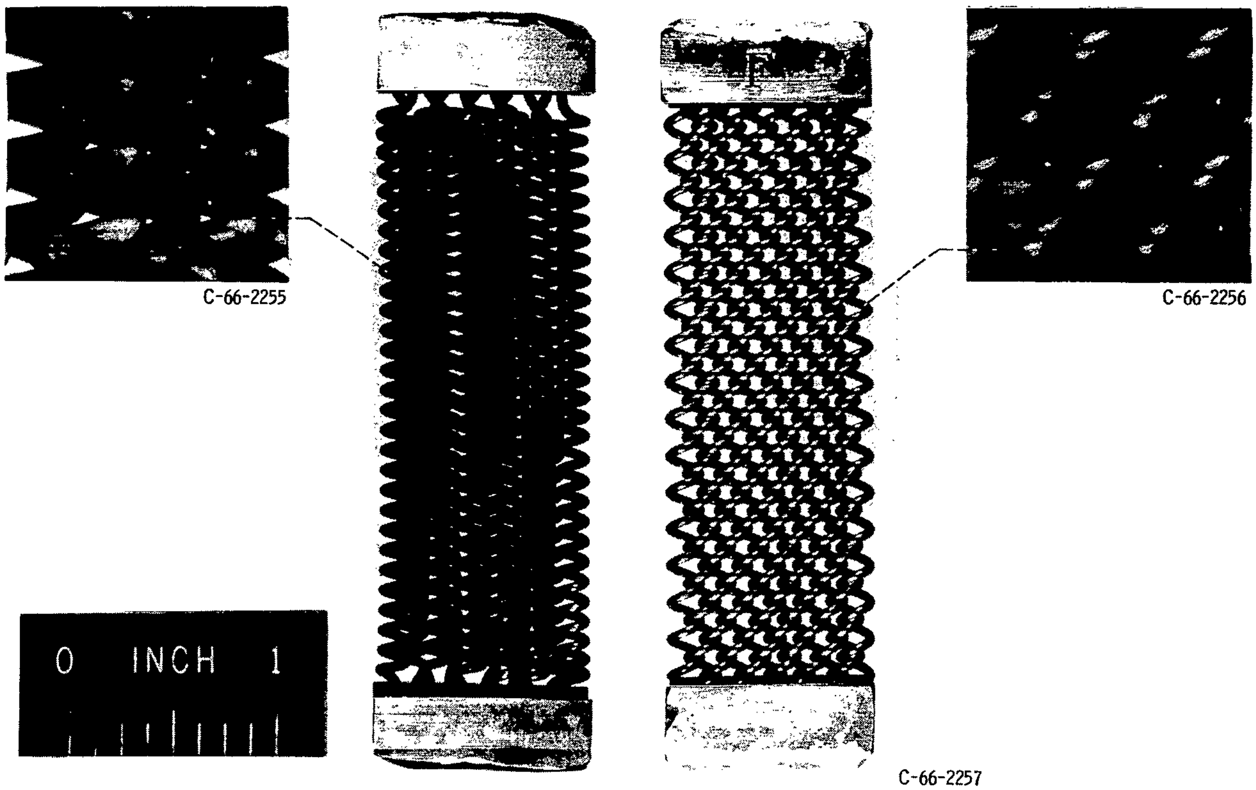


Figure 1. - Schematic diagram of test-section apparatus and location of instrumentation.



(a) Noninterwound coils. (b) Interwound coils.

Figure 2. - Tungsten wire matrix.

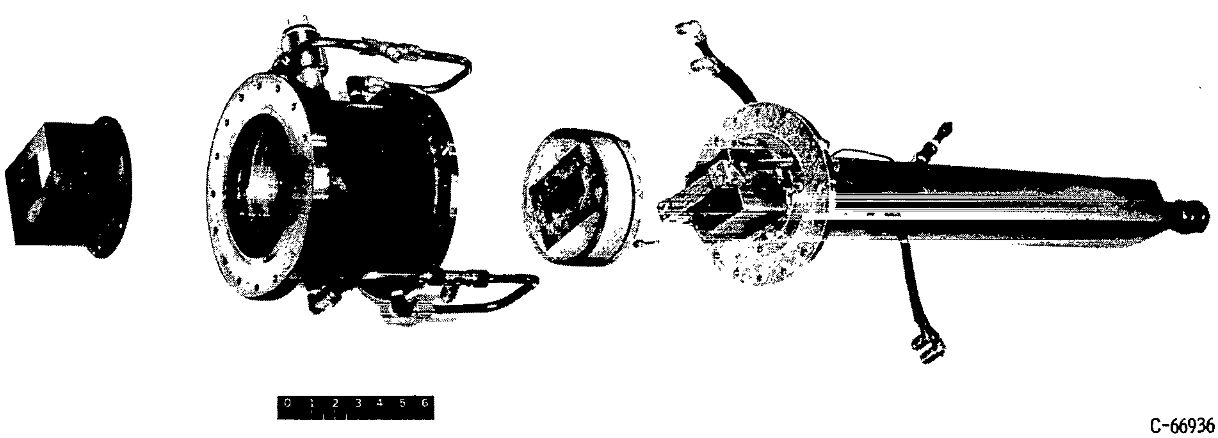


Figure 3. - Exploded view of test-section assembly.

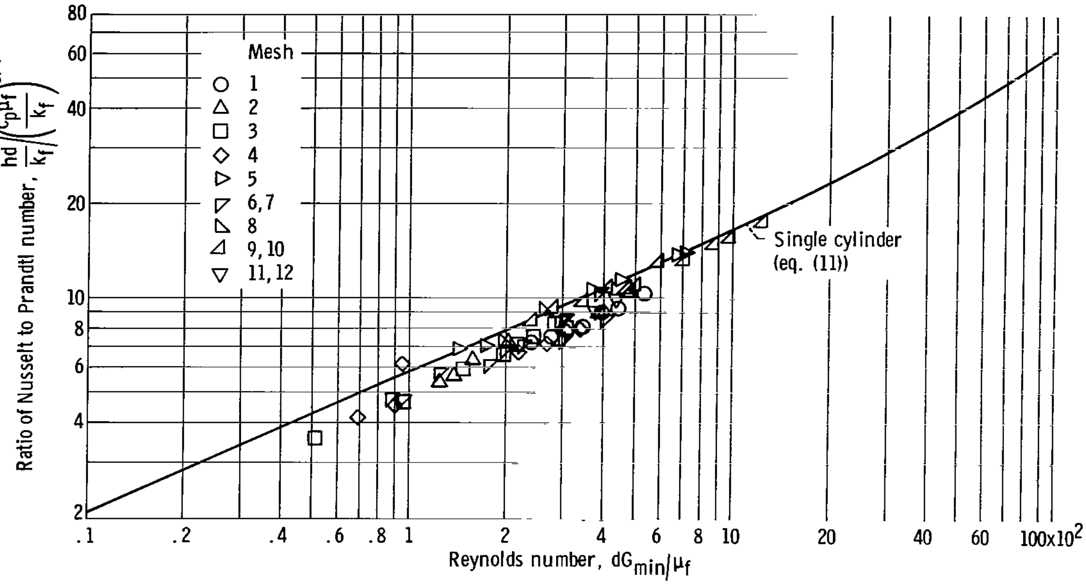


Figure 4. - Correlation of heat-transfer data for noninterwound coils.

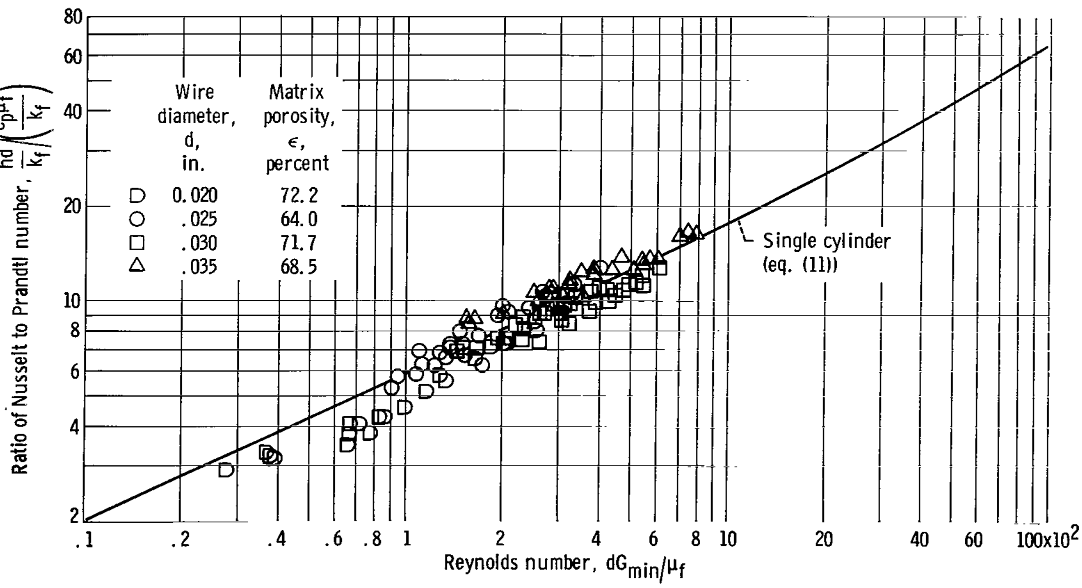


Figure 5. - Correlation of reference 3 heat-transfer data for interwound coils.

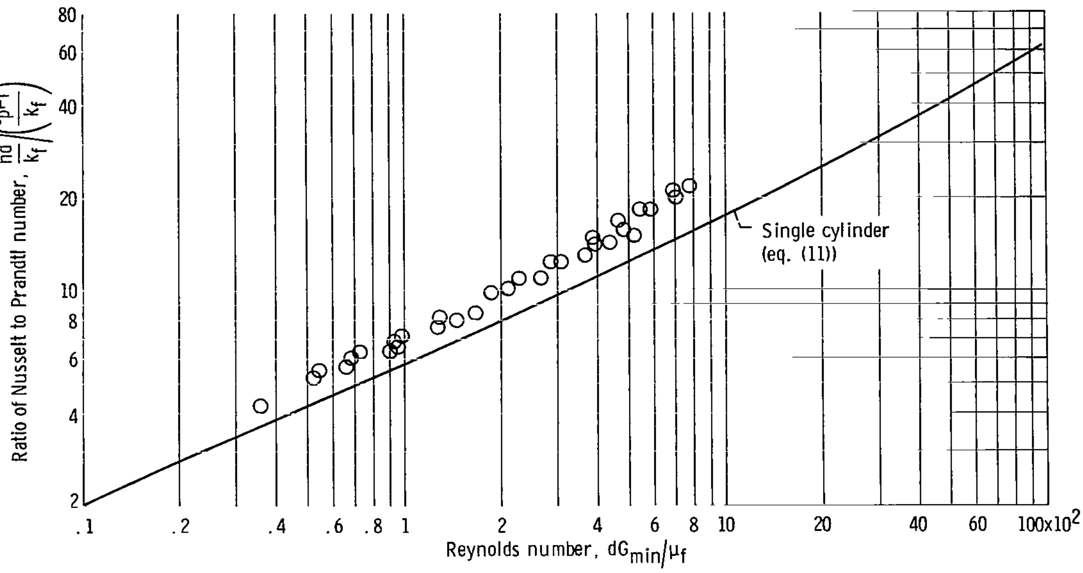


Figure 6. - Correlation of reference 2 heat-transfer data for banks of cylinders.

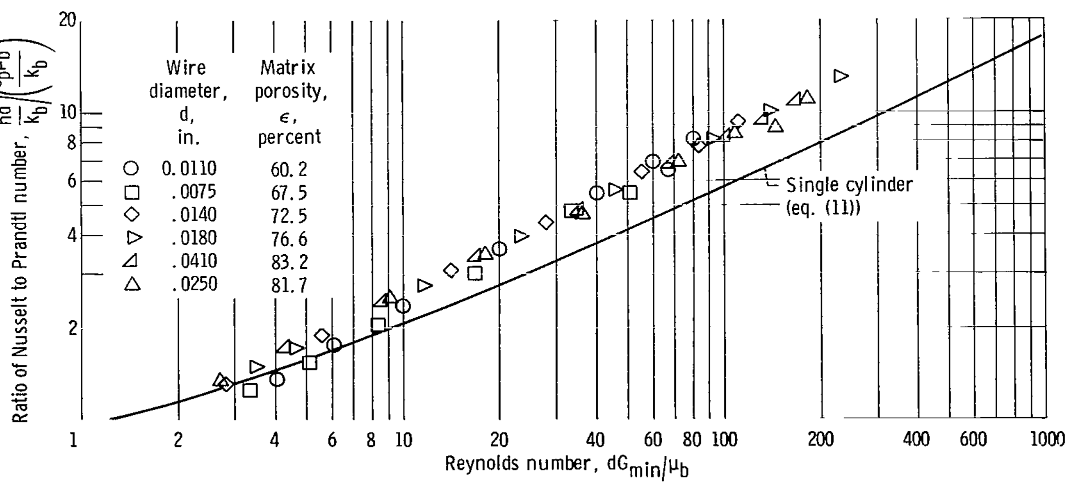


Figure 7. - Correlation of reference 1 heat-transfer data for woven-wire matrix.

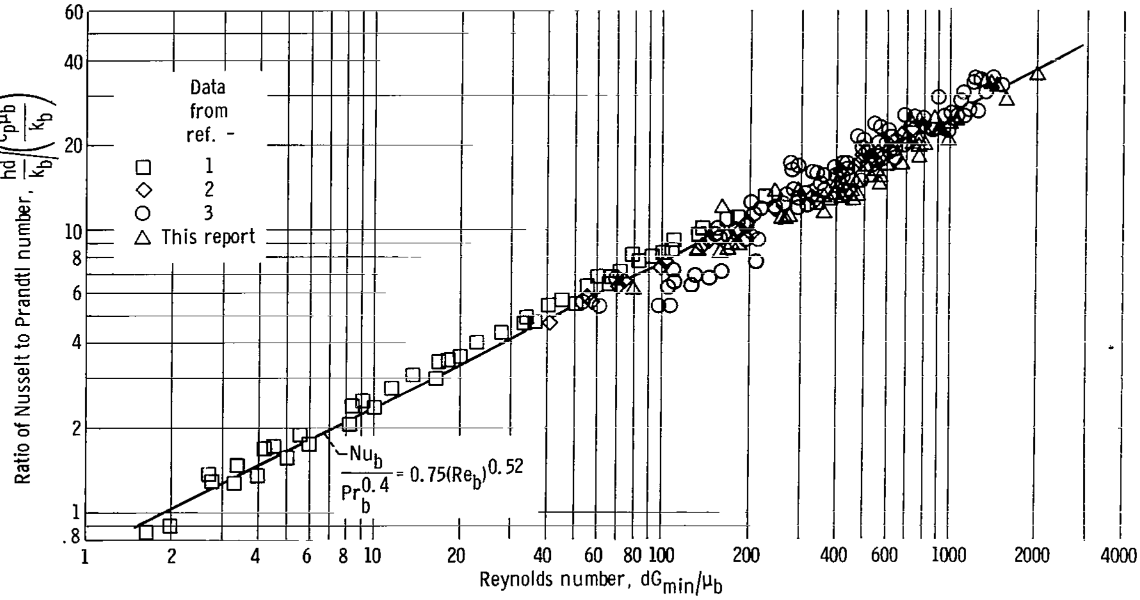


Figure 8. - Correlation of matrix heat-transfer data.

NASA-Langley, 1967 —— 12 E-3651