



EXPERIMENTAL STUDY OF HEAT CONDUCTION
THROUGH RAREFIED GASES CONTAINED
BETWEEN CONCENTRIC CYLINDERS

by

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ABSTRACT

Experiments were performed to measure heat conduction through rarefied gases at rest contained between two concentric cylinders. The test gases used were helium, neon and argon. The pressure was varied over a range that included free molecule, transition, and temperature jump conditions. The experimentally obtained heat conduction data were used to evaluate the results of the moment method proposed by Lees and Liu. Agreement between this method and the data was found to be within $\pm 2.5\%$ over the entire Knudsen number range covered in the experiments ($0.02 < Kn < 50$), assuming that the thermal accommodation coefficient at the inner cylinder remained constant over this range at its free molecule value. A comparison was also made between the data and the results of the temperature jump approximation, indicating that the heat conduction can be calculated by the temperature jump approximation within about 1% at Knudsen numbers less than ~ 0.02 . Comparisons were made between the data and the results of the free molecule theory and the mean free path method.

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I INTRODUCTION

There has been considerable interest in the problem of heat conduction through rarefied gases at rest. In particular, the problem of heat conduction through rarefied gases contained between two concentric cylinders has been widely investigated since, for practical reasons, this geometry has been most often used to measure thermal conductivities and thermal accommodation coefficients of gases. Due to the practical significance of the problem, various theoretical methods have been proposed in the past for describing heat conduction between concentric cylinders. Of these, the one recently developed by Lees and Liu (1) appears to be the most satisfactory. Utilizing the two sided Maxwellian distribution function and the Maxwell transfer equations, Lees and Liu derived an expression that predicts the heat conduction through monatomic gases from the free molecule to the continuum limit. In the analysis presented in Ref. 1 it was assumed that the inner cylinder, a fine wire, is placed coaxially in a large cylindrical tube and that the temperature difference between these is small. The analysis was based on complete thermal accommodation at the wire surface but this restriction was later removed by Hurlbut (2).

For satisfactory evaluation of this method, experimental heat conduction data would be required covering the density range from free molecule to continuum conditions. Much of the available heat transfer data has been obtained with either

monatomic or diatomic gases.* For example, heat conduction data can be extracted as a by product of the studies of the thermal accommodation coefficient of gases. However, most of these experiments (3-59) have been carried out in either the free molecule regime, where the mean free path in the gas is much larger than the characteristic diameter of the inner cylinder; or in the temperature jump regime, where the mean free path in the gas is much smaller than the characteristic dimension of the diameter of the inner cylinder. Consequently the heat transfer data is restricted to either low densities, the free molecule regime, or near continuum densities, the temperature jump regime.

Heat conduction data has also been obtained in the measurements of the thermal conductivities of gases. These measurements, utilizing the concentric cylinder geometry, have been carried out ever since the introduction of the "hot-wire" method by Schleirmacher in 1885 (60,61). This method has been further developed and used to make accurate measurements of most monatomic and diatomic gases (19,45,50, 51,62,85). Most recent of these are the measurements of Kannuluick et al (74,82)

Of these experiments discussed few were performed in the transition regime where the mean free path is of the order of

* See Appendix I for a comprehensive summary of many of these experiments on both monatomic and diatomic gases.

the diameter of the inner cylinder. In this regime, the most recent data were reported by Bomelburg (86) who, using air as a test gas, measured heat conduction from 1.25, 5, and 10 diameter Wollaston wires placed in 4 and 10 in. diameter bell jars. In these experiments Bomelburg assumed that thermal radiation and end-losses were negligible. Earlier experiments in the transition regime are described in Refs. 4-7, 28,43,44,52,73,74,87. These were for diatomic gases, with the exception of Schafer, Rating and Bucken's (28) experiment. They measure heat conduction through argon using a 0.00416 cm. diameter platinum wire placed in a tube of inner diameter 0.588 cm. The lowest pressure obtained in these experiments were 0.1 mm. Hg. Thus, the highest Knudsen number based on the diameter of the wire was approximately six. This Knudsen number is not sufficiently low to ensure free molecule flow, and therefore, the thermal accommodation coefficient was not measured but was assumed to have had the constant value 0.92 throughout the experiment.

Bomelburg's (86), and Schafer, Rating and Bucken's (28) data agree fairly well with the results of the method of Lees and Liu (1). The conditions of the experiments could be improved, however, and better experimental results could be obtained for comparison with the theory. This study was undertaken, therefore, with the aim of providing data for the entire pressure range in the hope of eliminating some of the shortcomings described above. In the experiments presented here, heat con-

duction was measured in monatomic gases at rest contained between two concentric cylinders, over a wide range of pressures including free molecule, transition, and temperature jump regimes, with particular attention to the transition regime. The data obtained were compared with the results of the method of Lees and Liu, the mean free path method, the free molecule theory, and the temperature jump approximation with the view of determining the applicability of these methods in different pressure ranges.

II EXPERIMENTAL APPARATUS AND PROCEDURE

A. Apparatus

Heat conduction measurements were made with helium, neon, and argon in an apparatus consisting of two concentric cylinders. The inner cylinder was a fine tungsten wire whose temperature and power loss were determined by passing a current through it and making the appropriate electrical measurements. The outer cylinder was of Pyrex glass maintained at constant temperature by an oil bath. The other experimental apparatus shown in Fig. 1 consisted primarily of (a) a vacuum system (shown at the left in the photograph) together with a gas supply and admitting system ; (b) the experimental test-tube and constant temperature oil bath (shown at the far right); and (c) the electrical equipment and instruments that supplied the currents to the experimental tube and made the necessary measurements.

The main vacuum and gas inlet systems, and the test-tube were mounted on $\frac{1}{2}$ inch aluminum rods supported on a frame of Dexion 225. The constant temperature oil bath was mounted on its own stand and had to be manually moved into position around the tube.

a. The Vacuum System

A schematic diagram of the vacuum apparatus and gas inlet system is shown in Fig. 2 .

The main vacuum system was constructed of all Pyrex. It consisted essentially of a Welsh mechanical pump (Model 1402-B) and an NRC 2" diffusion pump connected in series; two McLeod gauges (see Fig. 2), one a Cenco (Cat. No. 94151) and the other

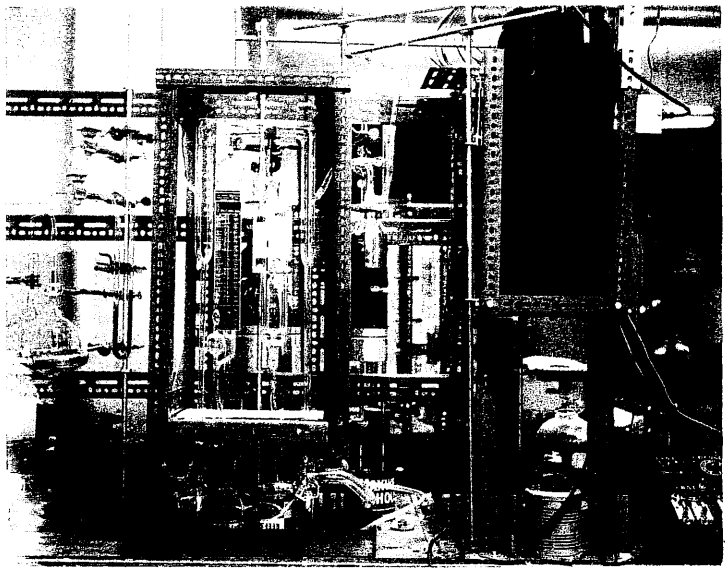


Fig. 1. Photograph of the experimental apparatus.

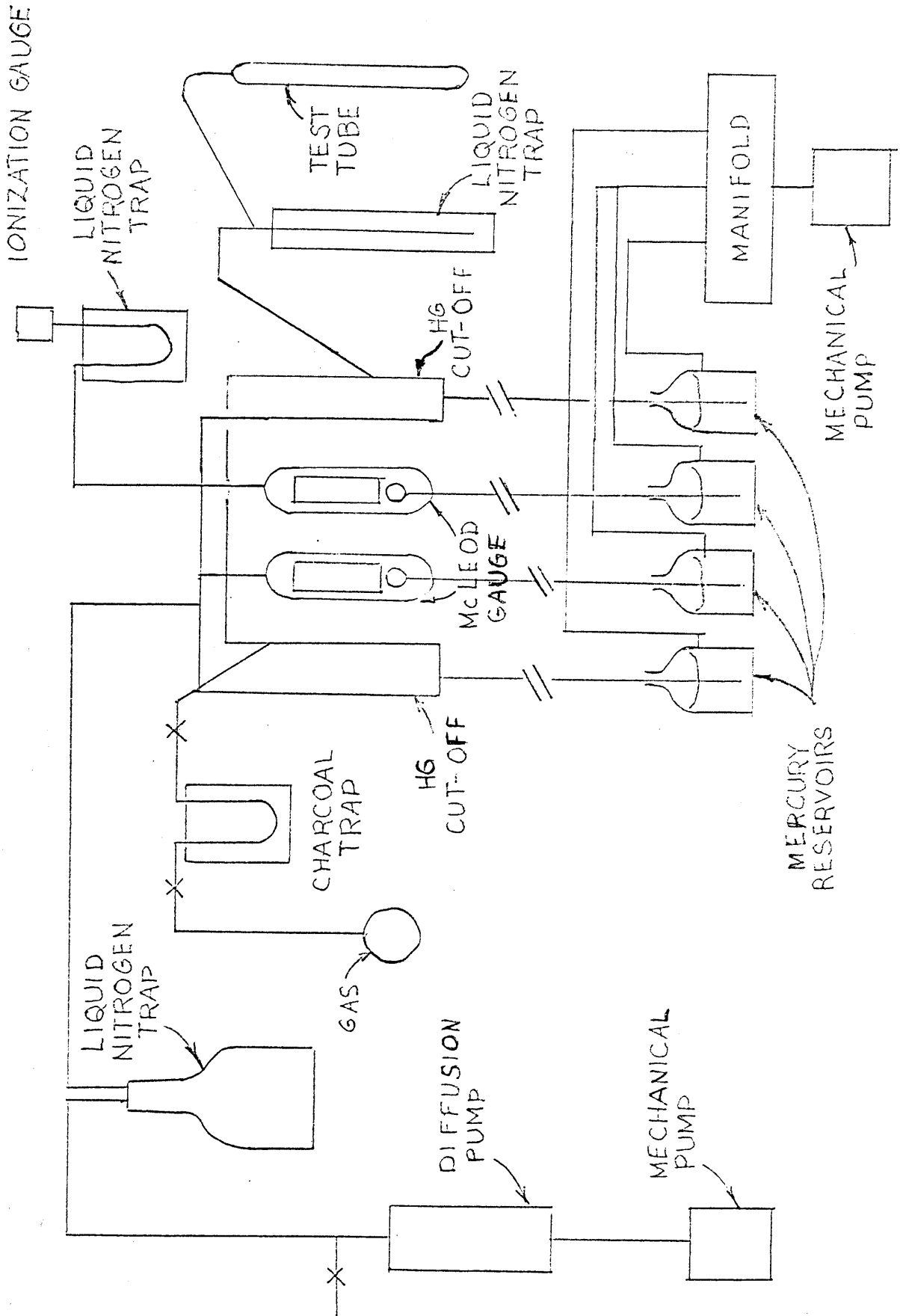


Fig. 2. Schematic diagram of vacuum system.

a Todd Universal Vacuum Gauge; two mercury cut-offs, one between the pumps and the gas supply system for isolating the gas supply system from the pumps, and the other between the experimental tube for isolating it from the rest of the system; two traps, one larger liquid nitrogen "finger" trap between the diffusion pump and the main vacuum system, and the other separated the experimental tube from the system by using liquid nitrogen or a dry-ice acetone slush. The operations of the Hg cut-offs and the McLeod gauges were controlled from four separate reservoirs of mercury, each of which could be opened either to the atmosphere or a Welsh mechanical pump (Model 1405-H) by means of a three-way stopcock.

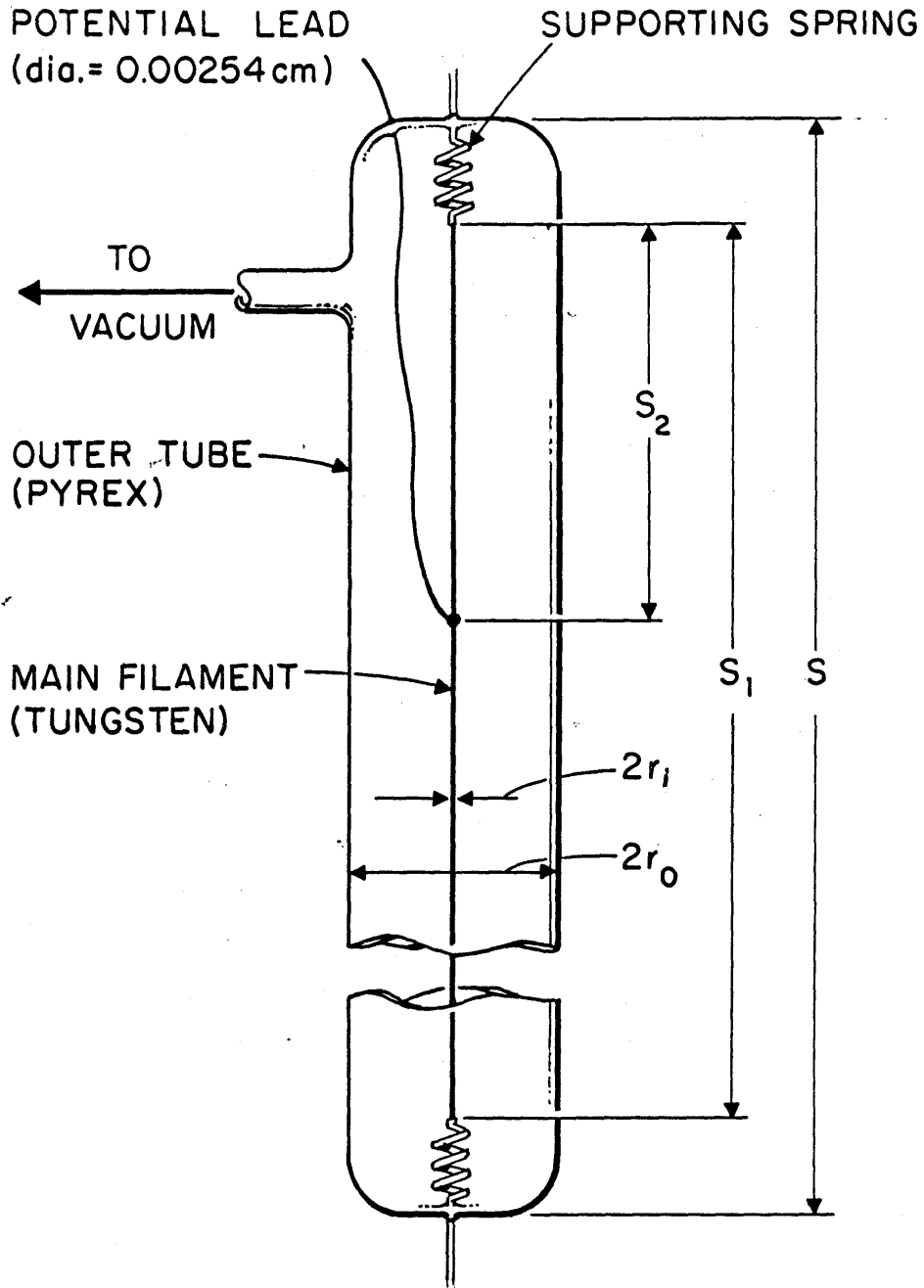
In all there were four pressure gauges attached to the system: an NRC(Model 710) ionization gauge, a Cenco McLeod gauge, a Todd Universal Vacuum Gauge, and a mercury U-tube manometer. These gauges covered the pressure range from 1×10^{-8} mmHg to 100 mmHg. The liquid nitrogen trapped NRC ionization gauge was used only to measure the lowest pressures the system obtained. With it pressures as low as 5×10^{-7} mmHg were recorded. The other three gauges were used to make pressure measurements during the experiments. The Cenco gauge was used from 0.0001 to 1.7 mmHg. and the Todd gauge from 0.0001 to 25 mmHg. The Cenco gauge was carefully calibrated with a standard C.V.C. (Type 619-100) McLeod gauge and found to be accurate to within $\pm 0.5\%$. At pressures from 5 to 25 mmHg, the mercury U tube manometer was used.

The U tube manometer consisted of mercury columns contained in 18mm Pyrex U tubes, one side of which was open to vacuum. The heights of the manometer Hg columns were compared with a cathetometer. Note that the range of the Todd gauge overlapped that of the Cenco gauge as well as that of the mercury U tube manometer in the pressure ranges from 0.0001 to 1.7 mmHg and 5 to 25 mmHg, respectively.

The gas inlet system consisted of the container of test gas, a cold trap, and two three-way mercury seal stopcocks. The test gas, helium, neon, or argon, was of the purest quality "Airco" in a one liter Pyrex container. These flasks were of the "breakoffsky" type, containing a small glass loop which was broken by means of a magnetically controlled iron slug encased in a glass jacket. The amount of gas admitted to the system was regulated by two three-way special grind mercury seal stopcocks (Apiezon "N" grease) after passing through a charcoal filled U tube cold trap at liquid nitrogen temperatures.

b. The Test Tube

The data presented in this thesis were obtained from two different tubes. The type of tube used is shown schematically in Fig. 3, together with a table of pertinent dimensions. In each tube a fine tungsten wire, axially supported in a precision bore Pyrex tube, served as the main filament. Two stretched spiral tungsten springs (.001"dia.) at the top and bottom of the filament served to compensate for thermal expansion during flashing. Tube A, used to make measurements with helium, had a main filament of standard tungsten wire. Tube B, used to make measurements with neon and argon, had a main filament of Sylvania Type NS-87 tungsten wire. The



	$2r_i$	$2r_o$	S	S_1	S_2	S_m
TUBE A	0.0081788	2.673	40.0	28.617	6.650	15.317
TUBE B	0.0085344	2.837	40.0	26.960	5.565	15.830

$S_m = S_1 - 2S_2$
ALL DIMS. IN CM.

Fig. 3. Schematic diagram of test tube.

diameter (0.0085344 cm.) of this wire was determined from the specifications of the density of tungsten (317gm/in^3) and mass of a 20cm length (21.91 mg/ 20 cm.) supplied by the manufacturer.

Each tube had a single potential lead of Sylvania type NS-86 attached to the main filament. The point of attachment (S_2 in Fig.3) was measured by a cathetometer after the tube was sealed. The potential lead was tied to the filament with an over hand knot. Subsequent heating of the filament produced a connection; Several times during the experiment, however, the potential lead became disengaged from the filament. It was found that the best procedure for making this connection was to flash both the filament and the potential lead to the glowing point. Both the potential leads and the main filaments were connected to glass press-seals containing tungsten leads for making the necessary inside to outside electrical connections. The use of potential leads permitted measurements from the center section of the main filament ($S_m = S_1 - 2S_2$, see Fig. 3). This is important because of the problem of determining radiation and end-losses from the filament. These quantities must be subtracted from the total power input to the filament to obtain the heat conduction. For a given average temperature of the filament, the combination of losses other than by conduction is given approximately by the power loss at the same temperature in vacuum. The reason for this approximation is that the temperature distribution along the filament is altered by gas conduction. The main effect for filament temperatures close to

the temperature of the outer wall of the tube is a change in the temperature gradient at the ends of the filament leading to a difference in end-losses. At some distance away from the ends of the filament, this change in gradient with conduction is decreased. Thus, by using potential leads and measuring power losses in only the central portion of the filament, the procedure of subtracting end-losses is more nearly correct.

The tube's outer surface was maintained at a constant temperature by immersing it in a constant temperature oil bath. This bath consisted of SAE 10 motor oil enclosed by an insulated tin can, 7 inches in diameter and $16\frac{1}{2}$ inches high. The oil was vigorously stirred with a home made stirrer driven by a "Variac" controlled A.C. motor at about 60 rpm. The temperature of the bath was maintained constant to within $\pm 0.02^{\circ}\text{C}$ by use of a Cenco 300watt knife type immersion heater controlled by a Princo "magnaset" thermoregulator. Frequent observations of ASTM calibrated total immersion mercury-in-glass thermometers showed the bath temperature to vary rarely more than $\pm 0.01^{\circ}\text{C}$. The bath temperature was $32.70\pm 0.02^{\circ}\text{C}$, $30.20\pm 0.02^{\circ}\text{C}$, $30.60\pm 0.02^{\circ}\text{C}$ for helium, neon, and argon, respectively. The temperature drop across the wall of the tube was considered negligible, the inside surface of the tube being assumed to be at the temperature of the oil bath. Thus a small temperature difference of about 7°C was maintained between the main filament and the inner surface of the test tube. With helium the temperature difference was $7.00\pm 0.02^{\circ}\text{C}$; with neon, $8.21\pm 0.02^{\circ}\text{C}$; and with argon, $7.81\pm 0.02^{\circ}\text{C}$.

c. Electrical Apparatus

There were two principal electrical systems connected with the operation of the tube. These consisted of the "measuring circuit" for determining the electrical characteristics of the filament necessary to establish its temperature and the power loss measurements necessary to calculate the heat conduction, and the "flashing circuit" for raising the filament to high temperatures. A diagram of these circuits is shown in Fig.4 .

Current for flashing was supplied by a D.C. generator controlled by a 22ohm variable resistor in series with three 62ohm resistors connected in parallel. At those times when the potential lead had to be reconnected to the main filament, another D.C. power supply was connected to the tube. However, with these arrangements for flashing the filament often vibrated violently, threatening to destroy the entire filament system.

Current for the filament and the measuring circuit was supplied by 6-volt storage cells. The current was determined accurately by measuring the potential drop across a one ohm standard resistance (L & N Type 4020-B). All voltage measurements were made with an L & N Type K-3 potentiometer, using an L&N Type 2430 galvanometer as a null indicator. These instruments were used with an Eppley Standard Cell (Cat. No.100). Both this standard cell and the standard resistance were accurate in the operating temperature range to at least six significant figures.

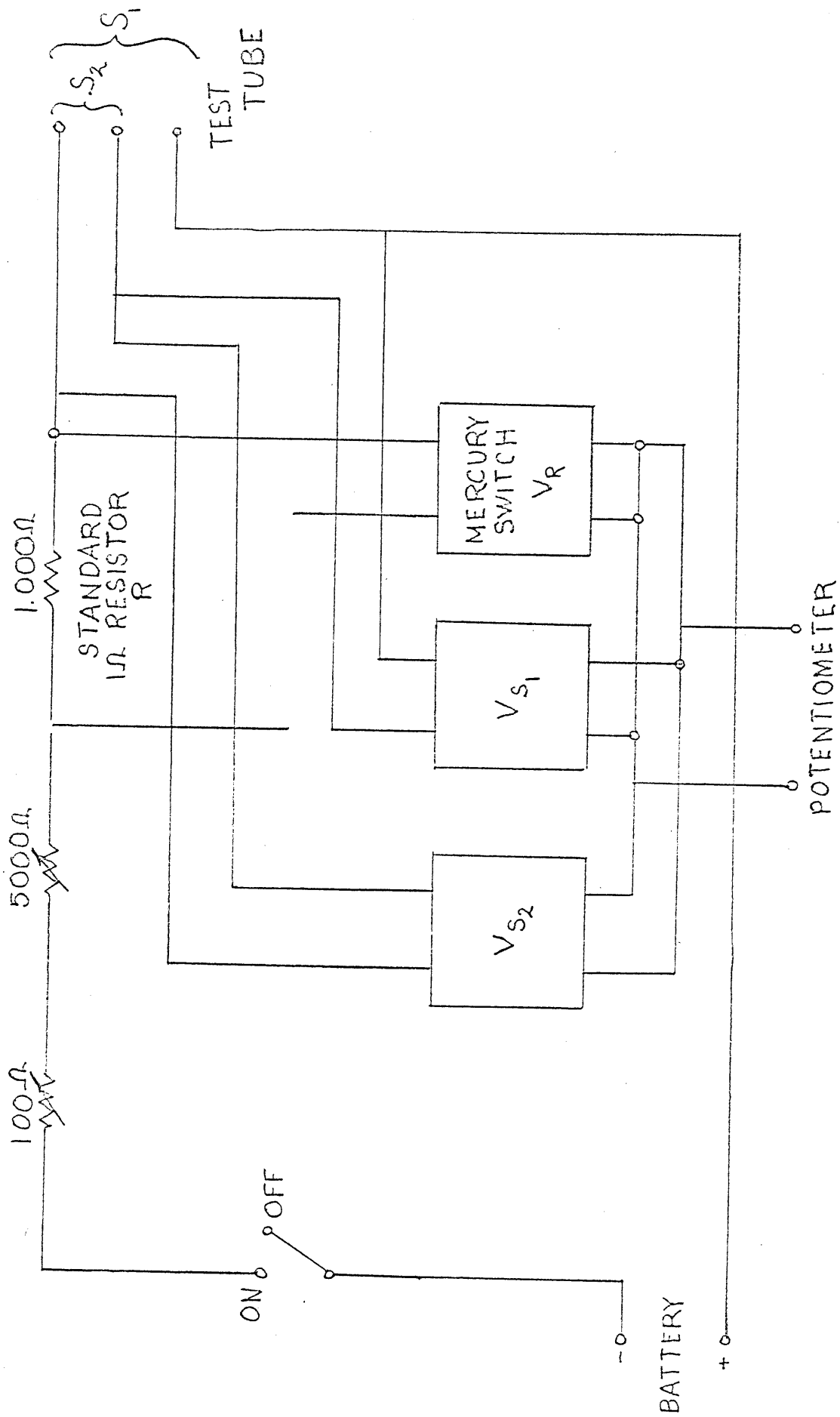


Fig. 4. Diagram of electrical measuring circuit.

B. Operating Procedure

After the tube was sealed to the vacuum systems the pump down was started (see Fig.2):

- a. The air-bleed valve was closed.
- b. Both Hg seal stopcocks in the gas supply system were opened.
- c. The Hg cut-off valves were opened to the pump.
- d. The valves of both McLeod Gauges were opened to the pump.
- e. Both pumps to main vacuum system and to the four mercury reservoirs were switched on simultaneously.
- f. If the pressure was not less than 30 microns within 5 minutes the entire vacuum system was checked for leaks.
- g. The bulbs of the Hg seal stopcocks in the gas supply system were evacuated.
- h. Dewars filled with liquid nitrogen were placed on the large "finger" trap separating the main vacuum system from the pumps, and on the cold trap separating the test tube from the rest of the vacuum system.

When the pressure was about 5 microns the test tube was torched to about 300^oC for about three-quarters of an hour. This initial bake out was to rid the tube of any water which might have collected in the system. The main filament was then annealed by flashing in vacuum at about 2300^oC for about an hour. This process also accomplished the joining of potential lead to the filament.

After such treatment the resistance of the filament at room temperature remained steady over the period of the experiments despite many other flashings at lower temperatures. The temperature of the filament during flashing was determined from tables given by Jones and Langmuir (88).

At this point it was found convenient to determine the electrical characteristics of the main filament. Thus the relationship between the temperature and resistance of the filament was found as follows: The system was shut down (see below for shut down procedure) to atmosphere pressure and the bath temperature set. When this temperature reached a steady value, small currents were passed through the filament and the resistance of the filament was plotted against power input for each current setting. This resulted in a linear plot which, when extrapolated to zero power input, gave the resistance of the filament at the given bath temperature. The values of the filament resistance at three different bath temperatures enabled calculation of the temperature coefficient of resistance β , in the temperature range from about 30 to 50°C. This coefficient was then used to calculate the temperature of the filament at any given resistance by using the relation

$$R = R_0 [1 + \beta(T - T_0)]$$

where R is the resistance of the filament, R_0 is the resistance of the filament at the lowest bath temperature used, T is the temperature of the filament, and T_0 is the lowest bath temperature used. A sample calculation is shown in Table I.

Table I

Sample Calculations for Heat Conduction

1. Argon	
2. Tube B.	
3. Pressure (P)	0.281 mmHg.
4. Potential drop across long section of filament (E_l)	0.134941 Volt
5. Potential drop across short section of filament (E_s)	0.036173 Volt
6. Potential drop across center section of filament ($E_m = E_l - E_s$)	0.098768 Volt
7. Potential drop across standard resistance (E_R)	0.050369 Volt
8. Current through filament ($I_R = E_R/1\Omega$)	0.050369 Amp
9. Resistance of center section of filament ($R = \frac{E_m}{I_R}$)	1.9609 ohm
10. Temperature coefficient of resistance (β)	0.0033772 ($^{\circ}\text{C}$) ⁻¹
11. Resistance of filament (center section) at bath temperature (R_b)	1.9105 ohm
12. Temperature of bath ($T_b \cong T_o$)	30.60 $^{\circ}\text{C}$
13. Temperature difference ($T_i - T_o = (\frac{R}{R_b} - 1)/\beta$)	7.81 $^{\circ}\text{C}$
14. Total power loss from filament ($Q_T = E_m I_R$)	0.0049774 watt
15. Power loss in vacuum (Q_v)	0.0001830 watt
16. Conduction from filament ($Q = Q_T - Q_v$)	0.0047944 watt

Following the calibration procedure, the system was again pumped down until a pressure of 5 microns was reached; the cooling water to the diffusion pump was turned on; and the diffusion pump started. At a pressure 5×10^{-5} mmHg, as read on the ionization gauge, the bake-out was begun. Two different types of ovens were used; cylindrical ones for the test-tube and cold traps, and an oven box for the McLeod gauges and the Hg cut-off. Both ovens were made out of asbestos with aluminum insulation; the removable box oven being constructed of $\frac{1}{4}$ inch thick asbestos board, with no. 20 nichrome wire, stretched between binding posts on the sides of the board, as the heating element. The ovens were designed to heat the Pyrex glass to 400°C and were regulated by "Variac" controls. All of the glass outside of the ovens was covered with heating tapes. First the oven around the charcoal cold trap in the gas supply system was heated from two to four hours to drive the bulk of the trapped gases out of the system. The other ovens were then slowly and uniformly raised to 350°C and the system was allowed to bake-out from ten to fifteen hours. The temperatures of the glass at various points in the vacuum system were observed with an L & N potentiometer (No. 8690) using copper-constant thermocouples.

Before all of the ovens are shut down the oven around the the trap nearest the test tube was removed and a dewar filled with either liquid nitrogen or a dry-ice acetone slush was placed around this cold trap. The other ovens were then turned off and the constant temperature bath placed around the tube. The bath temperature being set, the filament was flashed from

15 to 30 min. at about 1900°C in the presence of from 0.02 to 0.1 mmHg of the test gas. The test gas is then admitted to the system to the desired pressure. From the previous calibration a fixed filament temperature was decided for each gas. This required temperature was experimentally obtained by a trial and error procedure in which the filament's resistance was adjusted by passing various currents through it until the required resistance, and hence temperature was reached. After the total power input to the center section was measured as described in Ref. 89, the heat conduction was calculated by subtracting from the total power input the combination of end-losses and radiation losses. This sum of losses, referred to as power loss in vacuum, was determined as follows: The system was evacuated to approximately 5×10^{-7} mmHg, the operating bath temperature set, and the filament heated electrically to several different temperatures. At each temperature the current through the filament and its resistance was measured, to give the power input (power loss in vacuum) as a function of filament resistance at the operating bath temperature. A sample calculation of heat conduction using power loss in vacuum data is presented in Table I. Implicit in such calculations are the assumptions that losses measured in vacuum are nearly the same as those in the presence of the gas, and that heat transfer due to convection is negligible.

When all the measurements were made the vacuum system was "shut-down" as follows:

- a. The diffusion pump was shut off and allowed to cool (about 50 Min).
- b. All electrical apparatus was disconnected.

- c. The large dewar of liquid nitrogen on the main (finger) trap between pumps and vacuum system was removed.
- d. The McLeod gauges and Hg cut-offs were raised to a Height of about 30 cm.
- e. Both mechanical pumps were simultaneously shut off.
- f. The air-bleed value was slowly opened until the four mercury columns were lowered to their respective reservoirs.
- g. Steps d and f were repeated until the pressure in the system equalizes to that of the atmosphere.

The purpose of the above procedures was not to obtain the cleanest possible filament surface, but to attempt to maintain constant surface conditions throughout the experiment. In order to check the condition of the filament surface, the pressure in the test tube was reduced periodically to free molecule conditions and at these low pressures the thermal accommodation coefficients (α) were calculated using the formula (5).

$$\alpha = \frac{Q}{\Delta P A \Delta T} \quad (1)$$

where Q (watts) is the heat conducted from the filament, A (cm²) is the effective surface area of the filament, P (mmHg) is the measured pressure, ΔT (°C) is the temperature difference between the filament and the outer tube's surface, and Δ (watts/cm² - °C - mmHg) is the "theoretical free molecule heat conductivity" of the gas. During these checks, the values of the accommodation coefficient remained constant within the accuracies of the experiment.

III RESULTS

The heat conduction data presented in this section are for the monatomic gases helium, neon, and argon. These gases were chosen for the wide range in their thermal accommodation coefficient values as measured on clean platinum in the free molecule regime by Thomas and Brown (18). During the experiments, every effort was made to maintain the temperatures of the main filament and outer cylinder (T_i and T_o) at the constant values shown in Table II. The thermal accommodation coefficient on the surface of the filament was also constant throughout each experiment, as indicated by the periodic checks described in the previous section. If these conditions are fulfilled for a given gas, the heat conduction varies only with pressure. The primary purpose of this study was to investigate this pressure dependence in the free molecule, transition, and temperature jump regimes, with particular emphasis on the transition regime. Thirty-nine data points were taken with helium in the range 0.034 to 71.1 mmHg, corresponding to Knudsen numbers $Kn = 55.0$ and $Kn = 0.026$, where

$$Kn = \frac{L}{2 r_i} \quad (2)$$

r_i is the radius of the main filament, and L is the mean free path in the gas, evaluated at the temperature of the filament from a Table given by Dushman (90). Thirty-four data points were taken with neon in the pressure range from 0.0252 mmHg to 71.4 mmHg (Kn range 50.0 to 0.018) and thirty-three data points with argon from 0.0385 mmHg to 62.6 mmHg ($Kn = 17.0$ and $Kn = 0.010$). For each gas, about 2/5 of the measurements were

Table II. Parameters used for Figs. 5 , 7-11.

	Helium	Neon	Argon
1 Tube	A	B	B
2 $2r_i$ (cm)	0.0081788	0.0085344	0.0085344
3 $2r_o$ (cm)	2.673	2.837	2.837
4 S_m (cm)	15.317	15.830	15.830
5 T_o ($^{\circ}$ C)	32.70 ± 0.02	30.20 ± 0.02	30.60 ± 0.02
6 T_i ($^{\circ}$ C)	39.07	38.41	38.41
7 Q_{∞} (watts)	0.182304	0.070305	0.024500
8 Q_v (watts)	0.0004037	0.0001830	0.0001830
9 $(\alpha)_{avg}$	0.2831	0.4670	0.7328

Notes: Items 1 - 4 are shown in Fig. 3

Q_v is the power loss in vacuum.

$(\alpha)_{avg}$ was obtained from Eq. (1), and is the thermal accommodation coefficient used in computing (Q/Q_{∞}) in Figs. 7-11.

in the transition regime.

At each pressure the heat conduction (watts) between the main filament and the outer cylinder was determined by the procedure described in the previous section. The data are presented in Fig.5 . The heat conduction at infinite pressure (Q_{00} as $P \rightarrow \infty$ and $Kn \rightarrow 0$) will be required later in the analysis and was determined as follows: For each gas, the heat conduction (Q) was measured at several pressures (P) above 50 mmHg. Then $1/Q$ was plotted against $1/P$, resulting in a reciprocal plot similar to that obtained by Thomas and Golike (19). This plot, when extrapolated to $1/P = 0$, gave the values of Q_{00} shown in Table II.

The largest error associated with the measurement of Q (Fig.5) is approximately $\pm 0.4\%$; it occurs at low pressures where the heat transfer due to radiation and end-losses is of the same order of magnitude as the heat conducted through the gas. This error is considerably less at higher pressures as shown in Table III. The error in Q_{00} is approximately $\pm 0.5\%$. The largest errors in the pressure measurements also occurred at low pressures, and were approximately $\pm 4\%$ between 0.010 mmHg and 0.050 mmHg. The error in the pressure measurements is also reduced at higher pressures (see Table III). As a check on the aforementioned accuracies, the thermal conductivities (\bar{K}) of all three experimental gases were determined and compared to those found in the literature. For this comparison \bar{K} values were obtained by substituting the known length and radii and the measured Q_{00} and ($T_i - T_o$) values into Fourier's heat

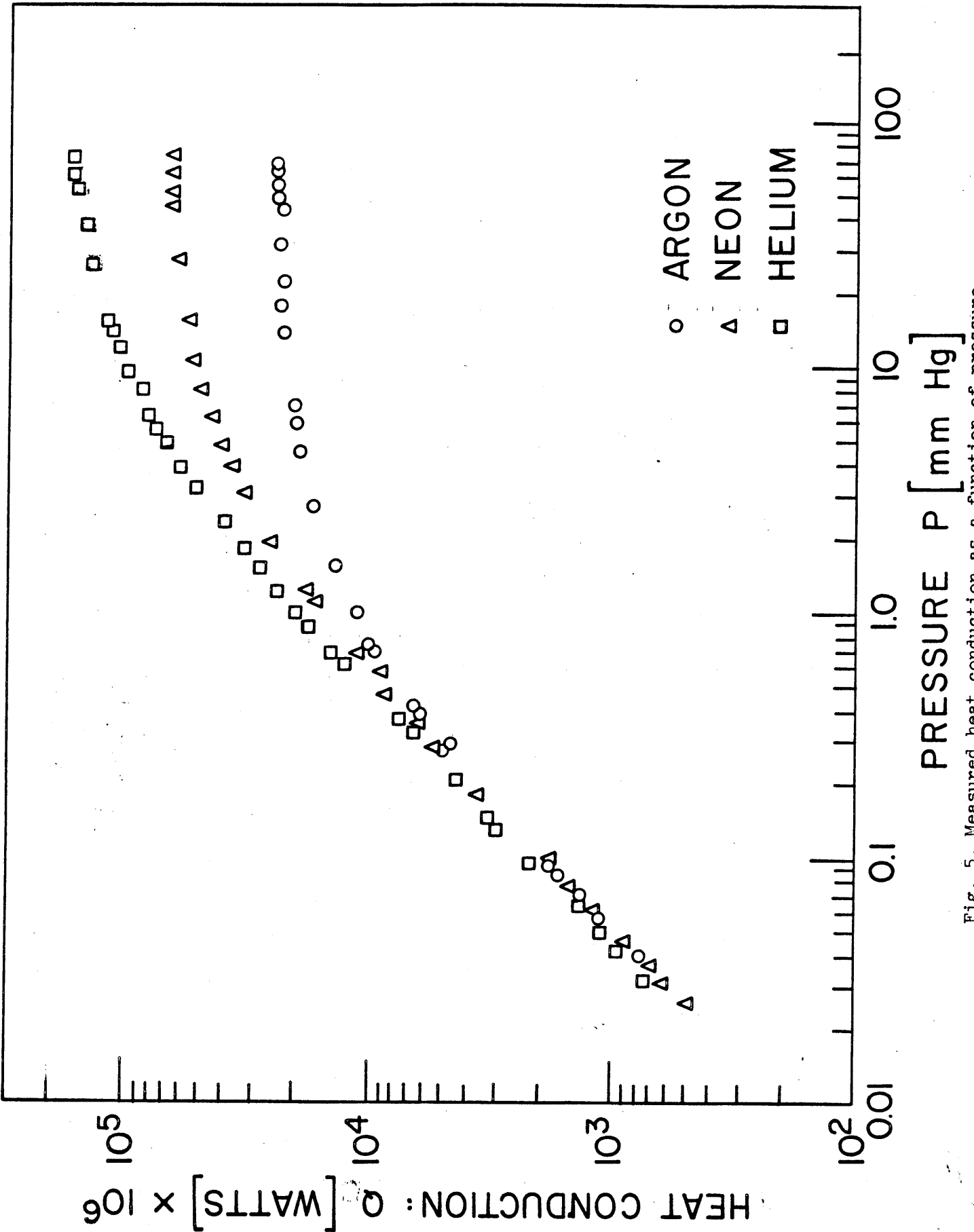


Fig. 5. Measured heat conduction as a function of pressure.

Table III. Estimate of errors in heat conduction and pressure measurements in different pressure ranges.

Pressure (mmHg)	Errors in P (%)	Errors in Q (%)
0.010 - 0.050	± 4.0	± 0.40
0.050 - 0.200	± 2.5	± 0.06
0.200 - 1.00	± 2.0	± 0.04
1.00 - 5.00	± 1.0	± 0.04
5.00 - 10.00	± 0.5	± 0.02
10.00 - 100.00	± 0.5	± 0.02

conduction equation. These analyses gave $\bar{K} = 3.708 \times 10^{-4}$, 1.962×10^{-4} , and 0.781×10^{-4} cal/sec - cm² - °C, for helium, neon, and argon, respectively. These values agree within -0.45% for helium, -0.20% for neon, and -0.90% for argon with those in Refs. 19 and 63 at the mean temperature $(T_i + T_o) / 2$.

The experimental data presented in Fig. 5 can now be used to evaluate the applicability of various methods predicting heat conduction in rarefied gases between concentric cylinders. In this investigation the methods studied were: 1) The method of Lees and Liu (1), henceforth referred to as the moment method (MM), 2) The mean free path (MFP), method, 3) The free molecule (FM) theory, 4) The Temperature jump (TJ) approximation.

Moment Method

Lees and Liu (1) evaluated the conductive heat transfer between concentric cylinders by dividing the gas molecules into two groups. Each had a different Maxwellian velocity distribution function. By substituting these functions into the Maxwell integral equations and assuming small temperature differences ($T_i/T_o \sim 1.0$) and large radius ratios ($r^* = r_o/r_i \gg 1$) they arrived at an analytical solution. This solution was derived for complete thermal accommodation at the inner surface and was extended to incomplete thermal accommodation at this surface (2, 91) yielding:

$$\frac{Q_{MM}}{Q_{\infty}} \approx \frac{1}{1 + \frac{15}{2} \frac{Kn}{\alpha} \frac{1}{\log r^*}} \quad (3)$$

where r^* is the radius ratio and α is the thermal accommodation coefficient at the inner surface. Eq. (3) applies over the entire pressure range from $Kn = 0$ to $Kn = \infty$.

Mean Free Path Method

Following the suggestion of Langmuir (66) and the adaptation of Springer and Ratonyi (91) the annulus can be divided into three regions. The two regions next to the inner and outer cylinder are assumed to have conductive heat transfer by the free molecule mechanism. In the center region continuum heat conduction is assumed. By combining the appropriate heat transfer equations one obtains:

$$\frac{Q_{MEP}}{Q_{\infty}} \cong \frac{\log r^*}{\log\left(\frac{r^* - 2Kn}{1 + 2Kn}\right) + Kn \frac{15}{2} \left(\frac{1}{\alpha} + \frac{1}{r^* - 2Kn}\right)} \quad (4)$$

Free Molecule Theory

In the free molecule limit where gas-solid interactions predominate ($Kn \sim 1$) for large radius ratios ($r^* \gg 1$) and small temperature differences, Knudsen's formula (3) may be combined with Fourier's heat conduction equation to give:

$$\frac{Q_{FM}}{Q_{\infty}} \cong \frac{1}{\frac{15}{2} \frac{Kn}{\alpha \log r^*}} \quad (5)$$

Temperature Jump Approximation:

When the mean free path is small compared to the diameter of the inner cylinder, Smoluchowski's temperature jump boundary condition (92) can be used. Applying Smoluchowski's formula to Fourier's heat conduction equation one finds (93):

$$Q_{TS} \approx \frac{2\pi r_i S \bar{K} (T_i - T_o)}{r_i \log r^* + g_i + g_o/r^*} \quad (6)$$

where S is the length of the cylinder, and g_i and g_o are the temperature jump distances at the inner and outer walls. For small temperature differences g_i may be replaced by (93):

$$g_i = \frac{2-\alpha}{\alpha} \frac{\bar{K}}{P} \left(\frac{\pi M T_i}{2R} \right)^{\frac{1}{2}} \left(\frac{C_v}{R} + \frac{1}{2} \right)^{-1} \quad (7)$$

In Eq. (7) M is the molecular weight of the gas, R is the molar gas constant, and C_v is the molar heat capacity at constant volume. Neglecting the term g_o/r^* and assuming $T_i/T_o \sim 1.0$, Eqs. (6) and (7) may be reduced to (91):

$$\frac{Q_{TS}}{Q_{\infty}} \approx \frac{1}{1 + \frac{15}{2} \frac{Kn}{\alpha} \frac{1}{\log r^*} \frac{2-\alpha}{\alpha}} \quad (8)$$

Eqs. (3, 4, 5, 8) assume that $T_i/T_o \sim 1.0$ and $r^* \gg 1$. The conditions in the present experiments were chosen to approximate these assumptions (see Table II).

The moment method may now be evaluated by comparing the measured and calculated heat conduction at various Knudsen numbers. In order to compute the heat conduction from Eq.(3) the thermal accommodation coefficient (α) must be known. In the derivation of Eq.(3), it was assumed that α was independent of Knudsen number. Therefore, in the following analysis it is assumed that α remained constant during the experiments and did not change with pressure. The accommodation coefficients used for each gas were calculated by applying the results of Eq.(1) to the data in the free molecule regime and averaging the results obtained (Table II). It should be noted that Eq.(1) would give slightly lower α values than Eq.(5) due to the assumption that $T_i/T_0 \sim 1$. Following the suggestions of Refs. 1,2,91 the Knudsen numbers limiting the free molecule regime were assumed to be those at which the heat conduction calculated by the free molecule theory and the moment method agree within 1%. These limiting Knudsen numbers are shown in Fig.6 for different thermal accommodation coefficients, and radius ratios. In this figure, the Knudsen numbers at which the results of the moment method agree within 1% with the results of the temperature jump approximation and with the continuum solution are also indicated..

The evaluation of the results of the moment method Eq.(3) with the data is presented in Fig. 7. An examination of the results in this regime shows that, with the exception of one point for each gas, all the calculated heat conduction values fall within $\pm 2.5\%$ of the experimentally determined values.

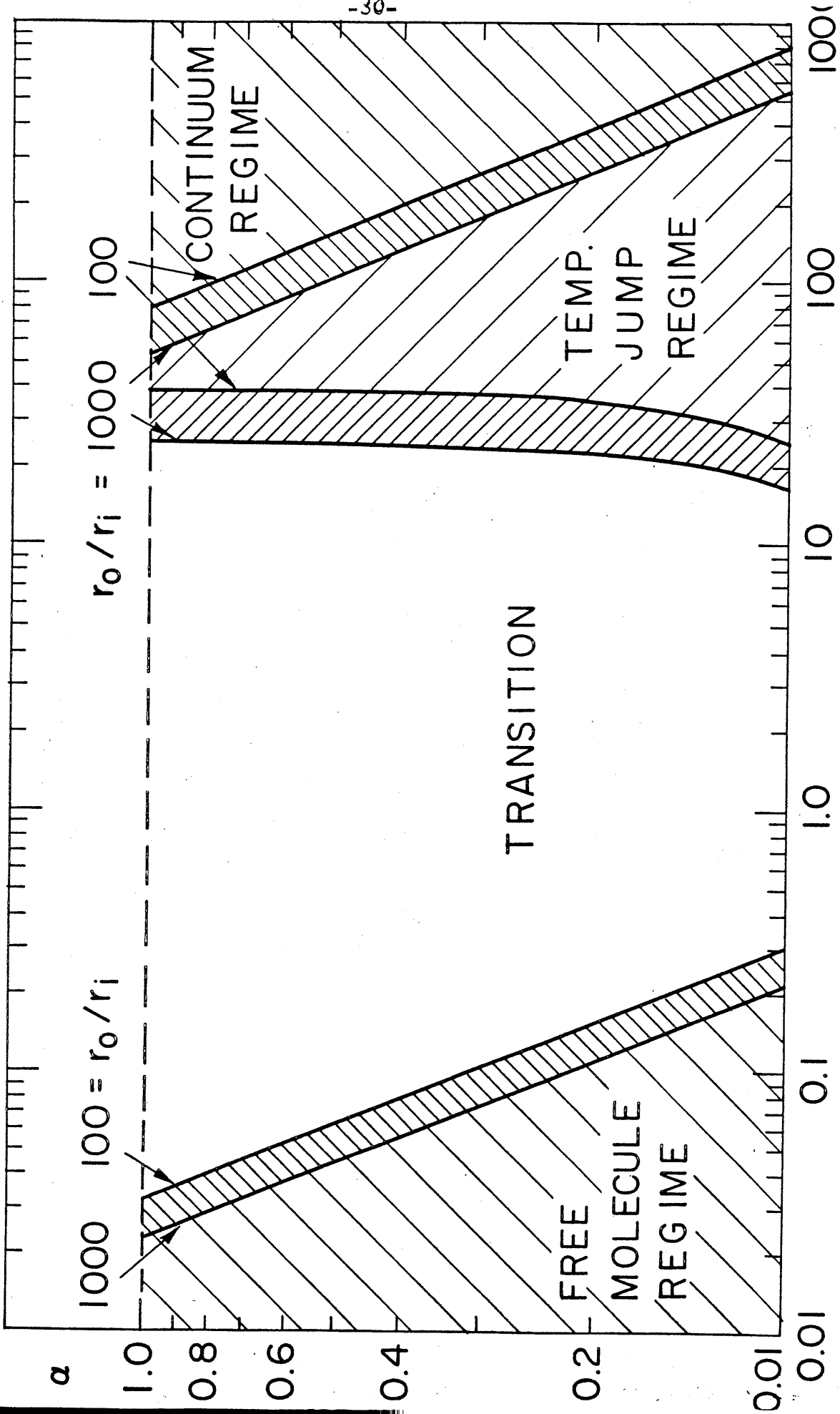


Fig. 6. Limits of various approximate methods.

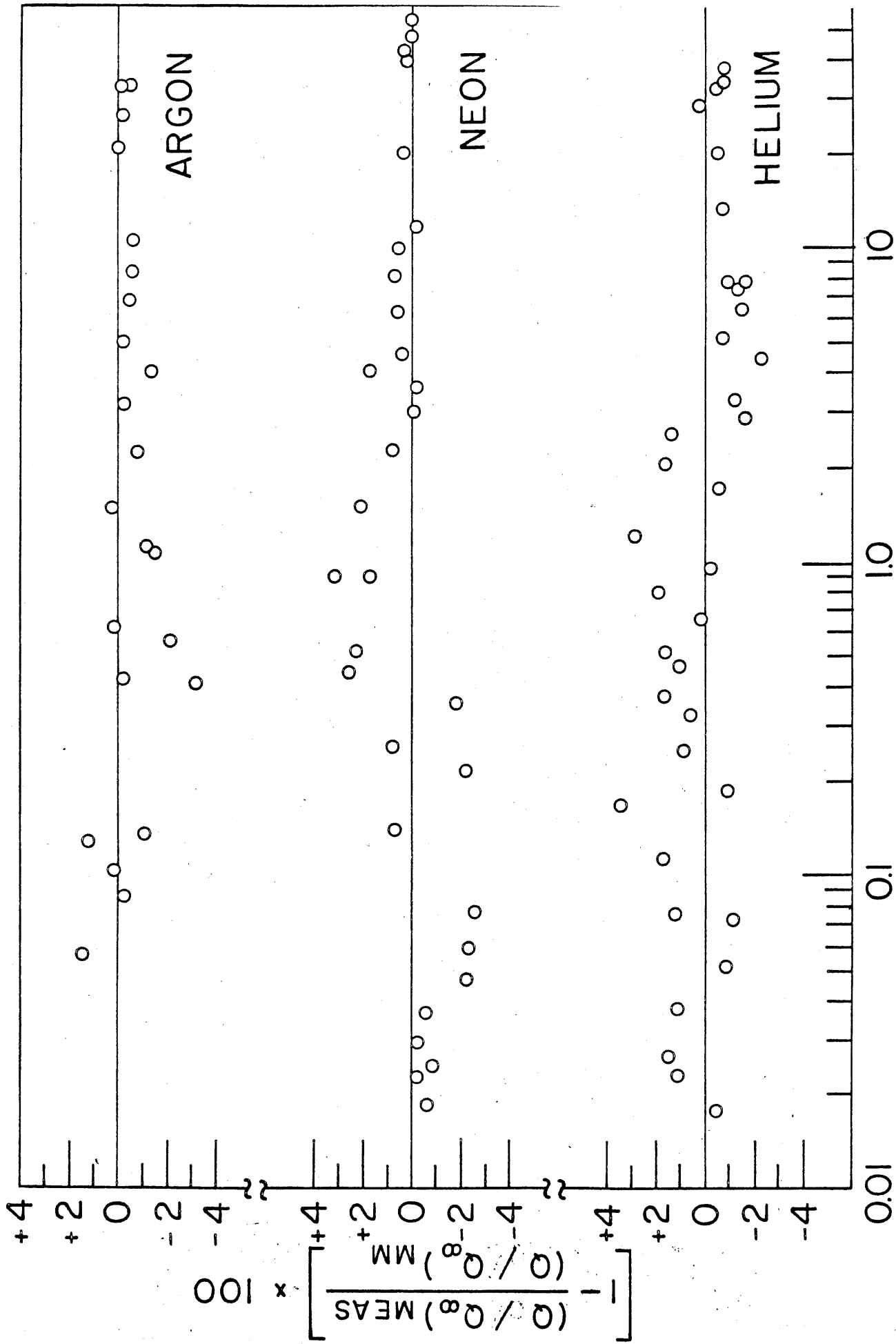


Fig. 7. Comparisons between the measured heat conduction coefficients and those calculated by the moment method.

This percentage difference is within the experimental errors given in Table III. These results suggest that the moment method can be used to calculate heat conduction to within at least $\pm 2.5\%$.

A comparison was also made between the data and the results of the temperature jump approximation (Eq.8) using again the thermal accommodation coefficients calculated by the free molecule theory and listed in Table II. This comparison (Fig. 8) indicated that heat conduction can be calculated by the temperature jump approximation within about 1% below $Kn \sim .02$.

Comparisons between the results of the four methods, the MM, MFP, FM and TJ methods, and the experimental data are given in Fig. 9. For clarity, the results are given only by average curves drawn between the data points. Fig. 9 indicates that the heat conduction calculated by the MFP, FM and TJ methods agree with the data only in the free molecule and temperature jump regimes. In the transition regime, as defined in Fig. 6, the data and the results of the MFP method agree within 6%. Neither the FM or TJ methods give good results in the transition regime.

All of the four methods (Eqs. 3,4,5,8) can be solved for the thermal accommodation coefficient. From the results of Fig. 9, one might expect good agreement of all the methods in the free molecule and transition regimes. Indeed in the past, the FM, TJ and MFP methods have been used to determine α in these regimes (59,94). The α values obtained by FM and TJ methods however, have generally been inconsistent (58,59) with the exception

● TEMP JUMP APPR.
○ MOMENT METHOD

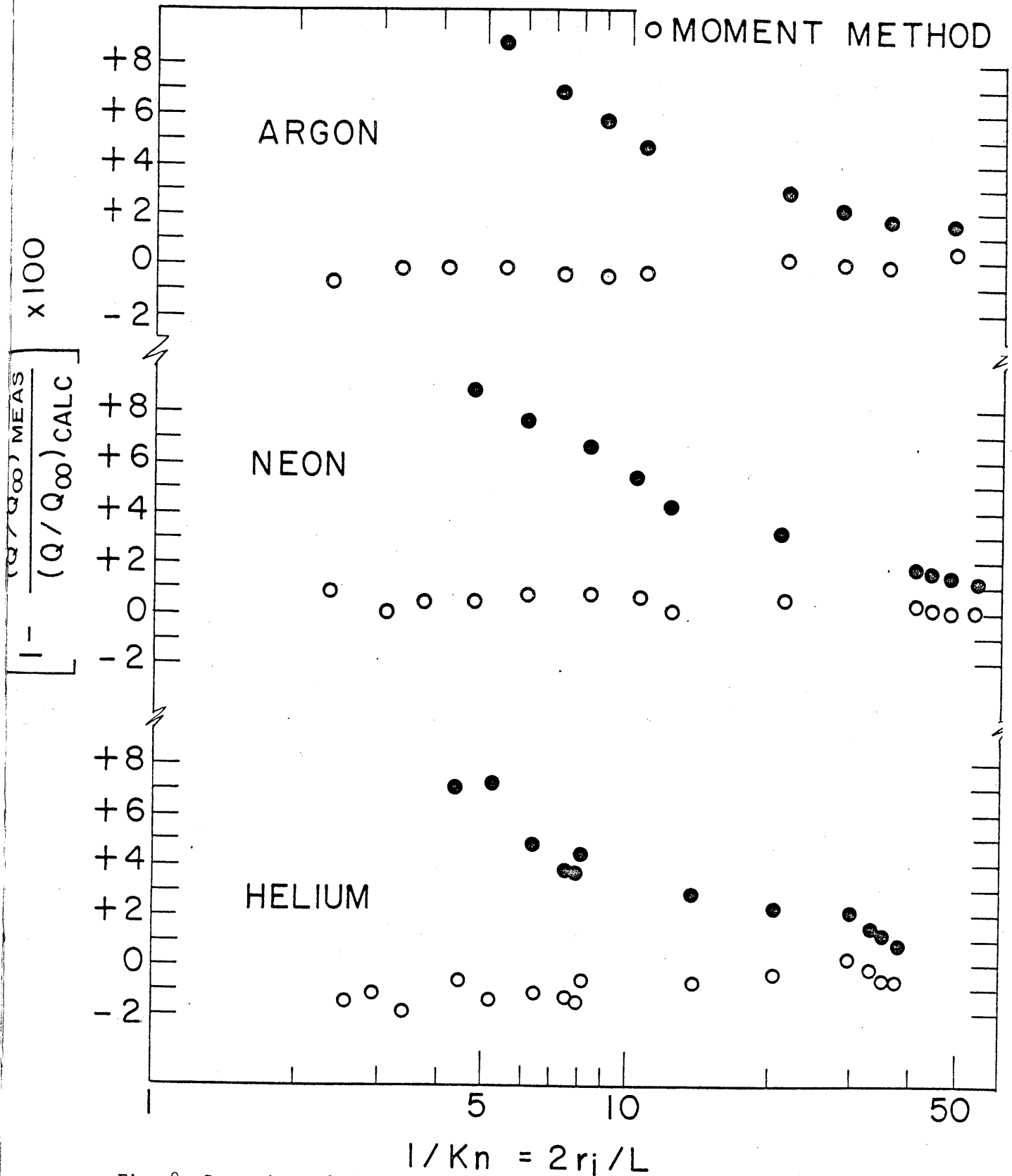
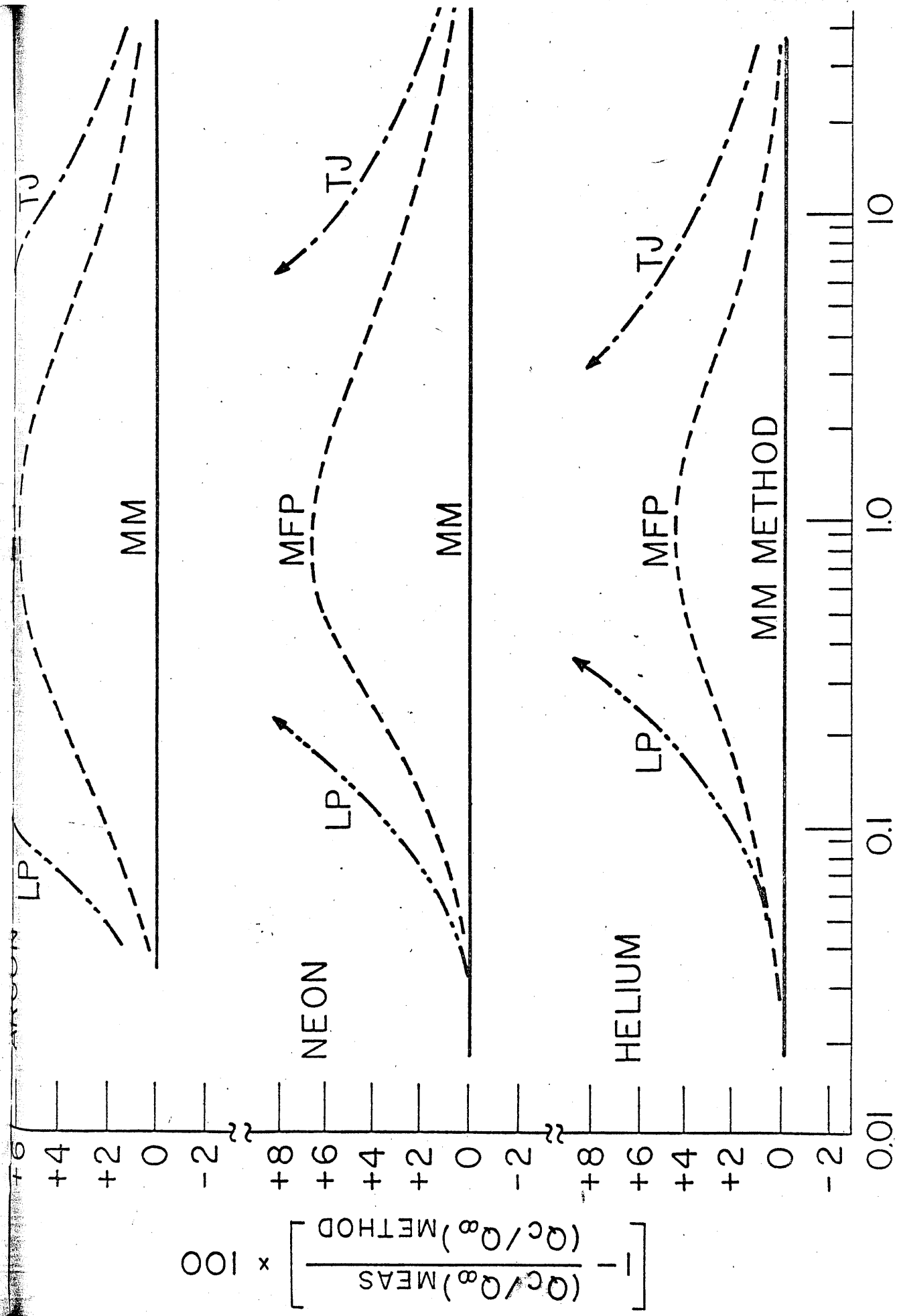


Fig. 8. Comparisons between the measured heat conductions and those calculated by the moment method and the temperature jump approximation.



$$1/Kn = 2r_j/L$$

Fig. 9. Comparisons between the measured heat conductions and those calculated by the MM, TJ, FM and MFP methods (avg. curves)

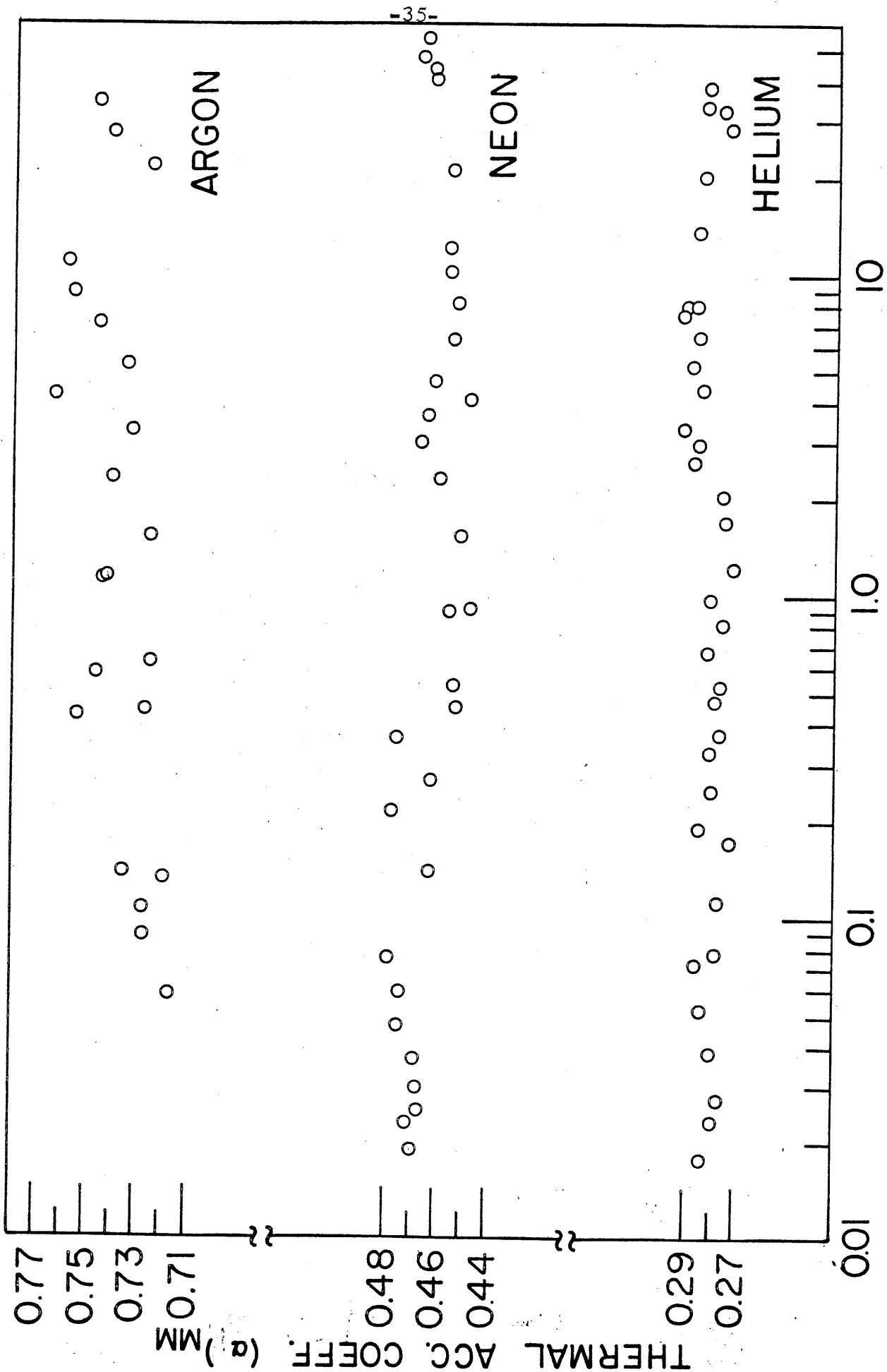


Fig. 10. Thermal accommodation coefficients as calculated by the moment method.

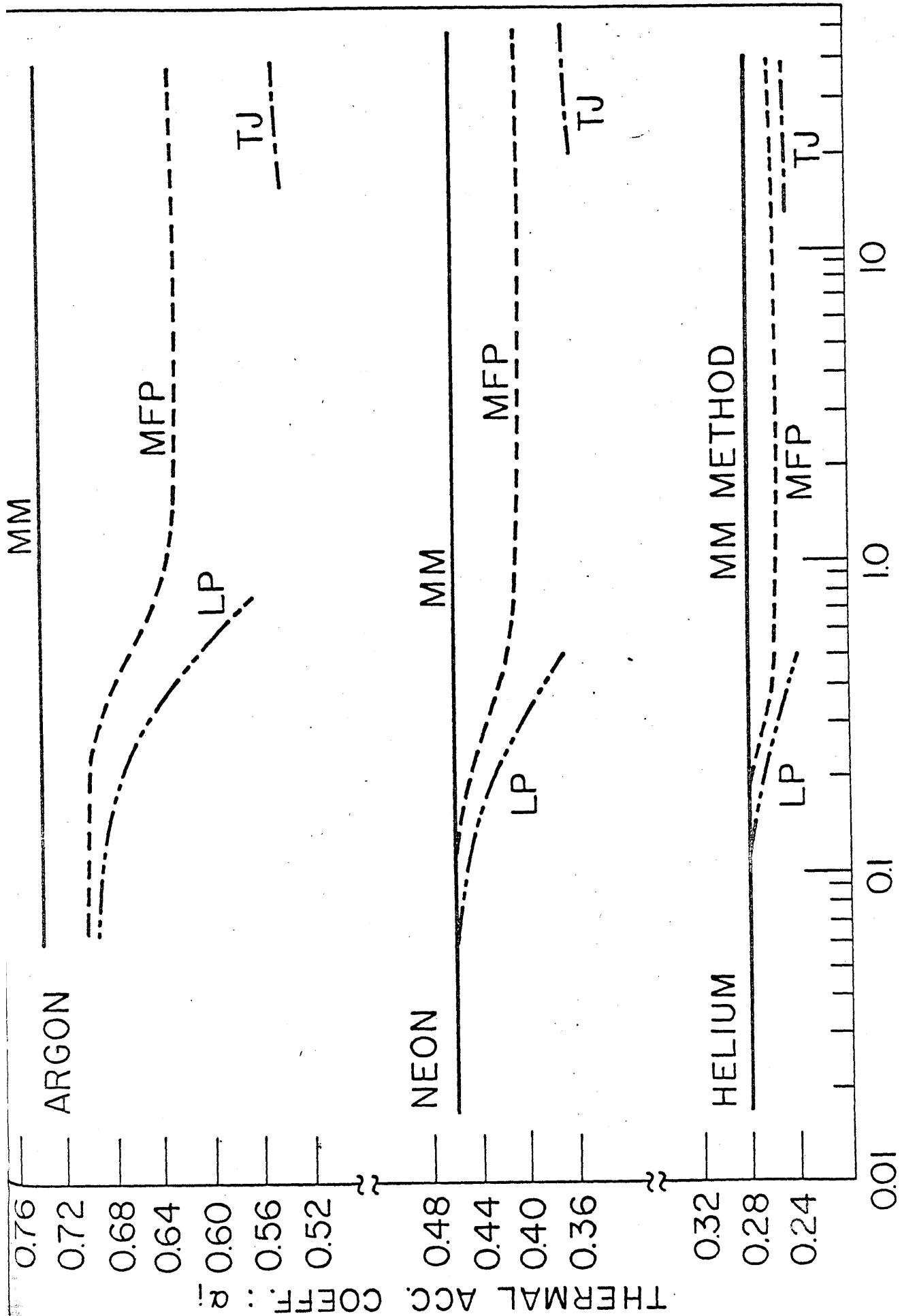


Fig. 11. Thermal accommodation coefficients as calculated by the MM, TJ, FM and MFP methods (avg. curves only).

of one experiment performed by Thomas and Golike (19). Furthermore, no thermal accommodation coefficient data has been reported in the transition regime. Therefore it would be very interesting to compute α values in the free molecule, transition, and temperature jump regimes using the four methods.

The results of these calculations are presented in Fig. 10 and Fig. 11. In Fig. 10 α , as determined by the moment method, is plotted against $1/\text{Kn}$ for all three test gases. These results appear to justify the assumption that the thermal accommodation coefficient remained constant during each experiment. As can be seen from Fig. 11, none of the other three methods gives such consistent α values over the entire pressure range. The α values computed by the FM and MFP methods approach those given by the MM in the free molecule regime only. The accommodation coefficients calculated by the TJ method are always lower than those given by the MM method, and in the free molecule regime, by the FM method. The data of Thomas and Golike (19) show the same trend. Here it is to be noted that at least in the range of these experiments ($\text{Kn} \sim 0.010$ to $\text{Kn} \sim 55$) the results of the TJ approximation as applied in the temperature jump regime do not agree with the results of the FM theory as applied in the free molecule regime.

APPENDIX I

The following is a brief summary of those technical papers which contain information about heat conduction in rarefied monatomic and diatomic gases.

Ref. No. , refers to number in bibliography

Gases , the type of gases reported in paper

Wire(diam) , the type and diameter of wire used in experiments

T_w , the temperature of the inner cylinder or wire

P , the pressure range covered in the experiments

Kn , the Knudsen range of the experiments

Purpose , the primary purpose for the experiments

Abbreviations used:

- a.c. , accommodation coefficient
- q , heat conduction
- ad. , adsorption
- u , unspecified data
- k , thermal conductivity

<u>Ref.</u>	<u>Gas</u>	<u>Wire(cm.)</u>	<u>T(°)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
4	H ₂	Pt. 0.000450	100	0.0025	3500	a.c.
	O ₂				4000	
	CO ₂				2800	
6	H ₂	Pt. 0.20	100	0.020	4	a.c.
	He				7	
7	H ₂	Pt. 0.00261	100	2.00 to 20.00	3 to 30	a.c.
	He				4 to 40	

<u>Ref.</u>	<u>Gas</u>	<u>Wire(cm.)</u>	<u>T(°C)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
8	He	W 0.007 cm.	u	0.044 to 0.10	-	a.c.
	He	Ni 0.007	u	0.044 to 0.10	-	a.c.
9	He	W 0.007	194	0.07 to 1.85	1 to 333	a.c.
	A			0.017 to 0.291	3 to 600	a.c.
10	He	same as in 9				
11	Ne	W 0.007	22	0.07	20	a.c.
12	Ne	W 0.007	30	0.07 to 1.85	0.8 to 20	a.c.
14	He	Pt. 0.0025	100	0.075 to 0.75	7.2 to 72	a.c.
	A				2.4 to 24	
	H ₂				4.8 to 48	
15	He	Pt. 0.0026	100	0.075	750	a.c.
	H ₂				600	
16	He	W 0.006	50	u	-	a.c.
17	He	Pt. 0.01	0	0.01 to 0.05	30 to 150	a.c.
	Ne				10 to 20	
	A				10 to 53	
	O ₂				11 to 54	
	CO ₂				6 to 34	
	H ₂				19 to 93	
21	He	Glass 1.5mm	80	u	-	a.c.
22	He	W 0.0049	u	u	-	a.c.
	A		u	u	-	

<u>Ref.</u>	<u>Gas</u>	<u>Wire (cm.)</u>	<u>T(°C)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
27	He	Ni 0.00423	u	0.001	-	a.c.
28	A	Pt. 0.00208	3,5	0.593 to 0.10	6 to 0.00195	a.c.
29	He	Pt. 0.00265	100	u	-	a.c.
36	H ₂	W 0.00779	500	0.20	25	ad .
37	H ₂	Pt. 0.005	20	0.03 to 0.3	60 to 600	a.c.
38	H ₂	Iron 0.0128	23	0.015 to 0.03	26 to 55	a.c.
39	H ₂	Pt. 0.00397	30	40 to 700	2.5 to 14	a.c.
41	H ₂	Pt. u	0	20 to 780	-	a.c.,,k
43	He	Pt. 0.244	60	0.0 to 0.38	∞ to 0.20	q
	H ₂				∞ to 0.10	
	Ne				∞ to 0.15	
	O ₂				∞ to 0.075	
	CO ₂				∞ to 0.033	
	A				∞ to 0.07	
44	Same as 43					
45	He	Pt. 0.00377	20	10 to 100	0.019 to 0.19	a.c.
	Ne				0.013 to 0.13	
	H ₂				0.011 to 0.11	
	O ₂				0.007 to 0.07	
	A				0.007 to 0.07	

<u>Ref.</u>	<u>Gas</u>	<u>Wire (cm.)</u>	<u>T(°C)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
45	CO ₂ Air				0.003 to 0.03 0.008 to 0.08	
47	He Ne H ₂	Glass 0.0038	30	0.04 to 0.10	4 to 10 6 to 15 6 to 12	a.c.
48	He Ne H ₂	Glass 0.0038	30	0.004 to 0.10	4 to 100 60 to 15 62 to 12	a.c.
49	He Ne H ₂	Glass 0.0038	30	0.007 to 0.60	0.55 to 70 0.42 to 30 0.4 to 28	a.c.
50	Ne	Pt. 0.005240	10	2.15 to 340	1.2 to 180	a.c.,k
51	He H ₂ CO ₂ O ₂ Air	Pt. u u u u	30	10 to 100	- - - -	a.c.,k
54	He H ₂	Iron 0.0096	30	0.00030 to 0.1	10 to 4000 10 to 3300	a.c.
56	He Ne A	Pt. 0.00137	3	0.007 to 0.5	20 to 1400 20 to 1300 10 to 700	a.c.

<u>Ref.</u>	<u>Gas</u>	<u>Wire(cm.)</u>	<u>T(°C)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
56	Kr				9 to 600	
	Xe				4 to 300	
	H ₂				15 to 1000	
	O ₂				10 to 700	
57	Same as 56					
61	H ₂	Pt. 0.08	10	0.07 to 680	0.00014 to 1.4	k
	Air				0.00006 to 0.6	
62	Kr	Glass 1.0	20	3.0 to 10.0	0.12 to 10	k
	Xe				0.07 to 20	
	He				0.4 to 40	
	Ne				0.3 to 30	
	A				0.15 to 15	
63	Ne	Pt. u	100	174 to 750	-	k
	He	u				
	A	u				
	Kr	u				
	Xe	u				
64	Air	Glass 0.4566	100	0.0013 to 770	0.001 to 60	k
65	H ₂	Glass 0.4566	100	0.0047 to 760	0.002 to 120	k
66	H ₂	Pt. 0.008	1300	0.015 to 750	0.01 to 500	a.c.,k
67	H ₂	Pt. 0.040	6	5.7 to 760	0.0002 to 0.04	k
	Air				0.0001 to 0.02	

<u>Ref.</u>	<u>Gas</u>	<u>Wire(cm.)</u>	<u>T(°C)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
68	H ₂ Air	Ni 0.041	30	0.0 to 500	0.0004 to ∞ 0.0002 to ∞	k
69	Air H ₂	Pt. 0.015	24	0.007 to 700	0.0005 to 50 0.001 to 100	k
71	CO ₂	Pt. 0.010	9	3 to 700	0.00005 to 0.01	k
72	Air	Pt. 0.010	16	2 to 700	0.007 to 0.25	k
74	O ₂	Pt. 0.010	13	10 to 800	0.006 to 0.05	k
75	Air H ₂	Ag 0.06	u u	0 to 60 0 to 480	- -	k
76	Air	Pt. 0.01	20	0.25 to ∞	0.0 to 13	k
77	CO ₂	Pt. 0.008	20	0.02 to 0.3	0.01 to 0.4	a.c., k
78	O ₂	Pt. 0.0053	u	1.0 to 500	-	k
79	H ₂	Pt. 0.0078	20	100 to 1000	0.001 to 0.01	k
80	CO ₂	u 0.05	200	u	-	k
81	Air	Pt. 0.024	20	6.15 to 196	0.001 to 0.03	k

<u>Ref.</u>	<u>Gas</u>	<u>Wire(cm.)</u>	<u>T(° C)</u>	<u>P(mm Hg)</u>	<u>Kn</u>	<u>Purpose</u>
82	A	Pt. 0.005	20	7 to 300	0.003 to 0.14	k
	Ne				0.006 to 0.28	
	He				0.001 to 0.5	
	Air				0.006 to 0.28	
	H ₂				0.005 to 0.26	
	O ₂				0.006 to 0.28	
83	Air	Pt. 0.06	6	10 to 700	0.00014 to 0.01	k
	H ₂				0.00025 to 0.016	
	CO ₂				0.00005 to 0.005	
	He				0.0003 to 0.02	
	Ne				0.0002 to 0.015	
	A				0.00014 to 0.01	
84	O ₂	Pt. 0.024	20	10 to 100	0.002 to 0.02	k
	CO ₂				0.0016 to 0.016	
	He				0.0005 to 0.005	
	H ₂				0.0004 to 0.004	
86	Air	Wollaston u 0.01		0.0 to ∞	0.0 to ∞	q
87	same as 66					

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