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CORRECTION OF PRESSURE DATA FOR THERMAL TRANSPIRATION EFFECTS IN PNEUMATIC LINES

by James A. Daggerhart

Prepared by
NORTH CAROLINA STATE UNIVERSITY
Raleigh, N. C.
for Langley Research Center

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SUMMARY

The thermal transpiration effect, or the existence of a pressure gradient along the length of a capillary tube in the presence of a temperature gradient, was experimentally examined for three capillary tubes. Length-to-diameter ratios of 43, 60, and 100 were examined. Stainless steel capillary tubes were used to simulate the conditions found in wind tunnels operated at low densities.

In order to remove the uncertainties in prior methods of measurement, in which the pressure at one end of the capillary is calculated from measurements made at the other end, a new technique was employed. This method allowed a direct determination of the capillary end conditions by utilizing a nude ionization gauge at each end of the capillary.

The test conditions ranged from continuum to free molecular flow, relative to the capillary tube, and in each flow regime the theoretically expected limits were found.

An empirical equation proposed by Liang is compared to the present results and found to be a valuable tool in predicting the transpiration effect in capillaries. Correction charts, based on Liang's equation, are presented and examples of their use in various situations are given.

The effects of capillary tube conductance and cleanliness on the time required to establish a condition of equilibrium throughout the capillary are also examined.

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INTRODUCTION

It has long been recognized that a tube experiencing a temperature gradient between the ends will also have a pressure gradient along its length when the molecular mean free path is comparable to the tube diameter. The existence of this pressure gradient may introduce serious errors into measurements made with a pressure gauge attached to a region of differing temperature if proper corrections are not made.

A simple technique used to correct for this effect at opposite ends of the pressure spectrum has been to apply the theoretical limits on this phenomenon in the continuum and free molecular flow regimes. For continuum conditions, where the mean free path is small compared to the tube diameter, the pressure is constant along the capillary and the thermal transpiration effect poses no problem in pressure measurement. For free molecular flow, where the mean free path is large compared with the tube diameter, kinetic theory predicts that the pressures on either side of an orifice are proportional to the square root of the temperatures existing on each side of the orifice. The pressure ratio may then be expressed as:

$$P_c/P_h = \left(T_c/T_h\right)^{\frac{1}{2}} \tag{1}$$

This relation is normally referred to as the free molecular orifice limit. Although strictly applicable only for an orifice, this relation has been employed to correct pressure indications at low system pressure levels without regard to the geometry of the particular capillary.

The use of the orifice limit as a pressure correction factor at low pressures had not been seriously questioned until the work of Edmonds and Hobson (1). Employing the absolute method of measurement, as outlined in Appendix A, with Pyrex capillary tubing, Edmonds and Hobson found that the orifice limit was not obtained for a capillary length-to-diameter ratio of 18.4. However, when this ratio was changed to 167, by holding the length constant, the expected orifice limit was found.

The behavior of the capillary having a length-to-diameter ratio of 18.4 was tentatively explained by a consideration of the molecule-wall interaction at low pressures. Using the model outlined in Appendix B, Edmonds and Hobson reasoned that the normally assumed cosine reflection from the wall was modified in such a way that a molecule entering the capillary from the hot region has a higher probability of transmission through the capillary than one entering from the cold region.

In an examination of the probability of molecular transmission through a capillary, the type of wall reflection is of critical importance. For the case of totally diffuse reflection, the geometry of the capillary, or more specifically the length-to-diameter ratio, is the determining factor in the value of the transmission probability. For an infinite length-to-diameter ratio, the assumption of diffuse reflection yields a molecular transmission factor of zero. At the opposite extreme, a length-to-diameter ratio of zero, an orifice, yields a transmission probability of unity. Specular reflection, on the other hand, always has a transmission probability of unity due to the velocity component directed along the capillary.

It is usually considered that, if the gas and wall temperatures are not widely different, perfect accommodation occurs with subsequent diffuse reflection.

As outlined in Appendix B, when a capillary connects a region of differing temperatures, the free molecular orifice limit may be modified by a ratio of transmission probabilities. However, when fully diffuse reflection occurs in the capillary, the probabilities of passage are a function of geometry alone and the ratio is unity. It should also be noted that, under the assumption of diffuse reflection, the length of the capillary or the presence of curves in the tubing do not affect the appearance of the orifice limit since the transmission probabilities are the same from either end.

Therefore, the orifice limit will be found as a limiting value in the presence of diffuse reflection without regard to the length. Long capillary lengths will, however, increase the time required for this equilibrium condition to be established.

In an extension of the earlier work by Edmonds and Hobson (1), Hobson (2) further examined the effect of the molecular reflection characteristics on the value of the thermal transpiration ratio at low pressures using a Pyrex capillary having a length-to-diameter ratio of 18.2. In order to provide an atomically rough surface on the Pyrex capillary walls, it was leached by a solution of 0.05 N hydrochloric acid for 100 hours at a temperature of 100°C. The orifice limit was then obtained for this capillary implying that diffuse reflection was occurring from the capillary walls. This result is in contrast to the earlier work of Edmonds and Hobson (1) which indicated that a combination of specular and diffuse reflection was present and was preventing the attainment of the orifice limit.

In order to correct for the transpiration effect, a reasonably simple method which is applicable to all gases is desirable. An empirical equation proposed by Liang (3) meets these requirements and provides a rapid means of predicting the transpiration effect in capillary tubes.

At the time of the formulation of Liang's equation, the validity of using the orifice limit as the low pressure bound on the transpiration effect had not been fully examined. As a result, the orifice limit, i.e. $P_c/P_h = \sqrt{T_c/T_h}$ was employed in Liang's equation to establish a bounding value for the transpiration effect. In view of the work of Edmonds and Hobson (1), however, if the molecular reflection characteristics are modified due to the temperature gradient, Liang's equation becomes invalid in the pressure region where free molecular conditions prevail relative to the capillary tube.

In the present investigation, the variation of the thermal transpiration ratio, P_c/P_h, was mapped from continuum to free molecular flow for three capillaries. Particular attention was given to the low pressure conditions in an attempt to determine if the molecule-wall interactions were affected in such a way as to modify the low pressure limit and thus cast doubt on the general usefulness of Liang's equation.

EXPERIMENTAL PROGRAM

The basic experimental apparatus consisted of two vessels connected by a capillary tube as shown schematically in Figure 1. The capillaries tested had a constant length of 47.6 cm. with diameters of 4.76, 7.93, and 11.1 mm. Each of the capillaries was installed in the system as received from the supplier with no attempt being made to roughen or polish the interior surfaces.

Since the testing procedure required that the system be isolated from the pumping system, the experimental system was fabricated entirely from stainless steel to minimize outgassing effects. All system closures employed copper compression seals and Heli-Arc welding techniques were used. The resulting system was found to have leakage/desorption rates on the order of 2×10^{-9} torr-liters/second.

In order to establish a temperature gradient along the capillary and to inhibit wall outgassing, one vessel was maintained at $300^{\circ}K$ while the other was immersed in a bath of liquid nitrogen. Helium was chosen as the test gas to remove the effects of gas condensation on the vessel walls. The use of helium had the added advantage of allowing, due to the relatively long mean free path, free molecular flow to be attained without the necessity of going to extremely low pressures.

In the initial design of the experimental system, it was felt that a need existed to measure directly the pressure ratio across the capillary tube. For this reason, it was decided to utilize ionization gauges at each end of the capillary as opposed to the absolute technique which employs one gauge and relies on computations to define the conditions at the other capillary end.

The reasoning for the use of such a technique, referred to as the two-gauge method, may be seen by an examination of the operating principle of an ionization gauge. The output of an ionization gauge is proportional to the molecular number density in the vessel in which it is mounted. Thus, the ratio of the number densities at each end of the capillary may be found by forming the ratio of the gauge outputs from each vessel. The pressure ratio may then be obtained by a knowledge of the temperature ratio across the capillary tube. This technique is valid so long as the gauges used are chosen so that any gauge constants associated with each gauge unit are essentially the same. The two-gauge technique also has the advantage of removing two factors which may affect the reliability of the absolute method. The effect of mass removal from the system by condensation does not influence the two-gauge method since it is not a function of the system conditions prior to cooling as is the absolute method. Gauge pumping effects are also negligible if the connecting capillary has a conductance of at least an order of magnitude greater than the gauge pumping speed. In this way, although the absolute system pressure may decrease with time, as a result of gauge pumping, an equilibrium condition will be maintained between the vessels.

In order to cover the pressure range from continuum to free-molecular conditions, two types of ionization gauges were employed. A standard Bayard-Alpert design ionization gauge was used for the pressure range of 10^{-3} torr and below while a compactly structured ionization gauge was employed to extend the measurement range to 1 torr.

In the course of the work, it became apparent that the indications of the high pressure ionization gauge could not, in all cases, be interpreted as a density measurement. A secondary investigation was therefore undertaken in an attempt to define the method of interpreting the output of this type gauge when placed in a cold environment.

The results of this work, Smetana and Daggerhart (4), indicate that the high pressure ionization gauge is sensitive to pressure rather than density for system pressure greater than 1 x 10^{-1} torr. However, the operating principle of an ionization gauge indicates that it should be sensitive to density rather than pressure, since it is a device which ionizes a fraction of the gas molecules present and indicates a pressure dependent on this density. Thus for a constant density, the pressure indicated by an ionization gauge should be the same regardless of any temperature variations in the system which would cause the absolute pressure to vary. It is felt that this density sensitivity will occur in the high pressure ionization gauge for very low pressures. Thus, there will be a transition from pressure to density sensitivity which is not well defined and for this experimental work, restricts the usefulness of this type of gauge in the two-gauge method.

As a result of this unexpected gauge behavior, it was necessary to employ the absolute method of measurement for system pressures greater than 10^{-3} torr. The difficulties associated with such a technique are discussed in Appendix A.

Presentation of Experimental Results

The variation of the thermal transpiration ratio, P_c/P_h, as a function of the absolute pressure level in the system is presented individually for each of the capillaries in Figures 2, 3, and 4. The pressure in the vessel maintained of 300°K was chosen as the abscissa as this would normally be the pressure monitored in a practical situation.

As was expected from kinetic theory considerations, the data tend toward the free molecular orifice limit for low values of the system pressure, corresponding to high Knudsen numbers. Also, for the continuum side of the pressure spectrum, the pressure ratio reaches a value of unity.

Although the results for the 7.93 mm. capillary are not complete enough to show the theoretically expected limits, it is anticipated that it will exhibit a behavior similar to the other capillaries. The lack of data for this capillary is due to the experimental techniques used early in this work as a result of the initial assumption that the two-gauge technique would be applicable over the entire pressure spectrum to be investigated. As a result of this assumption and the freedom of the two gauge technique from condensation effects, the standards of system cleanliness were not, in general, such as to allow the absolute method of calculation to be used. Therefore, only those experimental runs which were immediately preceeded by a period of extended bakeout, thereby meeting the conditions for cleanliness as required by the absolute method, were considered to be reliable for this capillary.

DISCUSSION OF RESULTS

In order to correct for the thermal transpiration effect, it is desirable to have a technique that is applicable to a number of experimental conditions and is relatively simple to use. To this end, several empirical methods have been proposed. These methods, however, are too complex to use readily, limited to a single gas, or do not reproduce the form of experimental data.

Thermal Transpiration Correction Charts

An equation proposed by Liang (3) as a result of fitting a curve to experimental data for several gases bypasses these difficulties and provides a means of rapidly predicting the transpiration effect for a number of different gases. To demonstrate the validity of this technique, Figure 5 presents a comparison of the present capillary data and Liang's equation in the form originally proposed as:

$$\frac{P_c}{P_h} = \frac{\alpha(\phi x)^2 + \beta(\phi x) + R_m}{\alpha(\phi x)^2 + \beta(\phi x) + 1} \qquad (2)$$

where $x = Pd$ (torr - mm)

$\alpha = 2.52$

$\beta = 7.68\ (1 - R_m)$

ϕ = pressure shifting factor and is a function of the particular gas used

$R_m = \sqrt{T_c/T_h}$.

The use of the product of the pressure and tube diameter, Pd, as a variable in the equation stems from the fact that the Knudsen number is usually taken as the correlating parameter for rarefied flows. The product of the pressure and tube diameter is proportional to the inverse Knudsen number and allows results from different experiments, for a particular gas, to be correlated without specifying a relation between the mean free path and the pressure.

It may be seen from Figure 5 that Liang's equation does have the capability of reproducing experimental data and suggests its usefulness as a means of predicting the thermal transpiration effect in capillaries. Other investigators, for example References 5, 6, and 7, have suggested modifications to this equation to fit particular sets of experimental data. The basic question then remaining is under what conditions may Liang's equation be used in its original form without having to select a modified form.

The experimental work performed by Liang did not include conditions to allow the free molecule orifice limit to be reached. As a result, the orifice limit, i.e. $R = \sqrt{T_c/T_h}$ was employed in Liang's equation to establish a low pressure bounding value for the transpiration effect. The more recent work of Edmonds and Hobson (1) with Pyrex tubing, however, suggests that the free molecular orifice limit may not be found as the limiting value in all situations, as a result of unequal molecular transmission probabilities, depending on which end of the capillary the molecule enters.

This phenomenon has the effect of increasing the minimum value of the transpiration ratio obtained when it is taken as the ratio of the pressure at the cooled capillary end to that at the warm end. This effect would then give values of the transpiration ratio which are higher than those predicted by Liang's equation in the pressure region where molecule-wall collisions predominate while leaving them substantially unchanged in the higher pressure ranges.

The work of Hobson (2) further substantiates the theory that the type of molecule-wall interaction is significant in defining the low pressure behavior of a capillary in the presence of a temperature gradient. By chemically roughening the surface of a Pyrex capillary, Hobson was able to define the low pressure bound for this capillary as being the orifice limit.

The results of the present work indicate, by the fact that the orifice limit is found to be the low pressure bound, that the surface of the stainless steel tubes employed was such as to allow diffuse molecular reflection to occur. Since the probability of molecular transmission through the capillary in either direction is then the same, the length-to-diameter ratio has no bearing on the final equilibrium pressure ratio across the capillary.

It is expected that, for most metals commonly used in vacuum system, the transmission probabilities will be equal in either direction allowing the orifice limit to be attained for sufficiently low system pressures. Then the use of Liang's equation, as originally formulated with the orifice limit as a bounding value, is justified in a prediction of the thermal transpiration effect in capillary tubes.

It should also be noted that Liang's equation is still useful, as pointed out by Edmonds and Hobson (1), even in a situation where the transmission probabilities are different, depending upon the direction of entry into the capillary, as in the case of untreated Pyrex tubing.

In this case the limiting pressure ratio existing across the capillary must be found experimentally for the condition of free molecular flow relative to the capillary. Liang's equation is then modified by replacing the orifice limit with that value found experimentally.

Liang's equation was formulated originally from data obtained, by the so-called relative method, in systems employing a temperature of $297^{\circ}K$ for the warm end of the capillary and temperatures of $77.3^{\circ}K$ and $195^{\circ}K$ for the cooled end. The relative method employs two capillary tubes of different diameters joined together. The junction of the two tubes is cooled and the pressure at the warm end of the small tube is determined directly by a pressure sensor. The pressure at the cooled end of this capillary is measured by means of a gauge attached to the large capillary, whose diameter is chosen so large that no lengthwise pressure gradient exists in it, at a point where the temperature is equal to that at the warm end of the small capillary. In Liang's derivation, the pressure used in the Pd variable is that indicated by the sensor with a temperature of $297^{\circ}K$. Thus, the pressure used to find the pressure-diameter product is that indicated by the measuring device, normally operated at room conditions, with the pressure at the cooled end of the capillary being found from the pressure ratio calculated by Liang's equation.

Since the low pressure magnitude of the thermal transpiration effect is fixed by the temperature ratio across the capillary, there would seem to be no theoretical basis to suggest that the variation of the effect with system pressure level would change its form as a function of the absolute temperature level. As a result, one would expect that, for a given temperature ratio, a plot of P_c/P_h versus the pressure-diameter product would not change its form if one capillary end were to be changed to each of the two possible conditions for a given temperature ratio while holding the other end at a fixed value of the temperature.

Since Liang's equation is a result of curve fitting, it is assumed to be valid for the situation in which the capillary end temperature is above the reference value of 297°K as well as when the end temperature is below this value.

For the present calculations the values of the pressure shifting factors employed were ϕ (helium) = 1, ϕ (argon) = 2.93, and ϕ (nitrogen) = 3.28, as given by Liang (3).

The charts resulting from the use of Liang's relation, equation 2, are presented in Figures 6, 7, and 8 for helium, argon, and nitrogen. For each of these gases, the transpiration effect has been calculated for the temperature ratios across the capillary: $T_c/T_h = 0.6$, 0.5, 0.33, and 0.25. Since a constant gauge reference temperature of 300°K has been assumed, each value of the temperature ratio gives rise to two system conditions. For example, considering a temperature ratio of 0.5 will yield system temperatures of 150°K and 600°K for a reference temperature of 300°K. Thus each curve will apply to two operating conditions.

It is anticipated that a gauge reference temperature other than 300°K will modify the results predicted by Liang's equation since it is based on this reference value. Since this effect is not yet well-defined, the results presented here are strictly applicable only to a situation in which the pressure gauge is held to a temperature of 300°K.

In each of the charts, the value of the correction factor, P_c/P_h, is determined only by the value of the pressure-diameter product. In forming this product, the proper pressure to use is that indicated by the pressure sensor at the capillary end maintained at 300°K. Although the length of the capillary tube does not affect the value of the correction factor, it does alter the time required for the equilibrium value of the correction factor to be attained after a change is made in the system. For a given capillary diameter, for example, the shorter the capillary, the less the time required from the point of some change until the system can again be considered to be in equilibrium.

Some caution must be used in the application of the charts to a particular installation since the system temperature at the point where the true pressure is desired may either be greater or less than the 300°K reference temperature of the pressure sensor. In the event that the system temperature is less than the reference of 300°K, P_h refers to the pressure indicated by the sensor while P_c refers to the true pressure at the system conditions. However, if the system temperature is greater than the reference, P_h refers to the system conditions and P_c refers to the pressure indicated by the sensor.

As an example of the application of the charts, consider a system operating in a helium environment with a 5 mm. inside diameter capillary tube connecting the pressure sensor to the system. For an indicated pressure 2×10^{-2} torr, the corresponding correction factor for a temperature ratio of 0.5 is R = 0.767. There are then two cases to be considered as given below:

Case I. System temperature greater than that existing at the sensor

$$T_{sys} = 600^{o}K$$

$$P_{sys} = (P_{sensor})/R$$

$$P_{sys} = (2 \times 10^{-2} \text{ torr})/0.767$$

$$P_{sys} = 2.61 \times 10^{-2} \text{ torr}$$

Case II. System temperature less than that existing at the sensor

$$T_{sys} = 150^{o}K$$

$$P_{sys} = (P_{sensor})\ (R)$$

$$P_{sys} = (2 \times 10^{-2})\ (0.767)$$

$$P_{sys} = 1.53 \times 10^{-2} \text{ torr}$$

Factors Influencing Time to Equilibrium

When a pressure gauge is attached to a pressure source by means of a capillary tube, a knowledge of the response characteristics of the combination is of great importance. For example, if a pressure sensor is connected to several different sources by means of a manifold, the sensor will indicate a pressure different from the actual value at the source immediately after switching to a new source even in the absence of any temperature discontinuities. The same situation will occur if the sensor and source are initially in pressure equilibrium and the source conditions are suddenly changed. In either situation, a knowledge of the time required for the sensor to adjust to the new conditions is of great importance either to accurately determine the new pressure or to size a sensor-capillary combination for a particular application.

In a process where the pressure fluctuates rapidly, for example, a sensor-capillary combination requiring a relatively long time to adjust to changing pressure conditions would be of little use in reproducing these changes.

When a pressure gauge is combined with a capillary, the time required for the gauge indication to change in response to varying conditions at the capillary end is determined by the capillary conductance as well as the volume enclosed by the pressure gauge. For a given gas and capillary diameter, the conductance, or the ease with which gas passes through the tube, is determined by the length of the capillary and the value of the absolute pressure at which the system is operating. The dependence on the length is such that an increase in length is accompanied by a decrease in the capillary conductance while an increase in the system pressure level increases the capillary conductance.

In a consideration of the response, or rate of exhaust of a volume connected to a capillary, it is normally assumed that a pump is attached to one end of the capillary and has a pumping speed sufficiently high to maintain essentially a zero pressure at the pump inlet with respect to that existing in the volume. In this way, the quantity of gas passed through the capillary conductance S may be written as $S(\Delta P)$ with ΔP being the pressure drop across the capillary. This reduces to simply SP with the assumption of negligible pressure at the pump inlet.

If it is further assumed that any capillary outgassing and inertial effects in the gas motion may be neglected, the rate of exhaust of the volume V may be found by equating the rate of gas removal from the volume, V(dP/dt), to the quantity of gas flowing through the capillary. This results in a relation, as given by Dushman (8), in the form:

$$P_2 = P_1 e^{-St/V} \tag{3}$$

where P_1 = initial pressure existing in the volume

P_2 = pressure existing in the volume after a time t

S = capillary conductance.

In an equation involving an exponential variation with time, a quantity designated as the time constant is usually defined. The time constant is defined as that period of time required for the pressure to change to 1/e of its instantaneous value at any time t or, in other words, to complete 63.2 percent of the total change. In the case of equation (3), the time constant is V/S seconds.

Therefore, considering the concept of the time constant, the response of a capillary-gauge combination to changing conditions is in the form of an exponential approach to equilibrium. In a practical situation, allowing three time constants to elapse, which is equivalent to 95 percent of the total change, after a change in the capillary end conditions has occurred, should insure that an equilibrium condition again exists between the gauge and the capillary end.

To properly define the time constant for a particular capillary-gauge combination, both the gauge volume and the capillary conductance must be known. Due to the fact that the enclosed volumes of various gauge types may differ appreciably, the following calculations are based on a constant gauge volume of one liter.

In an analysis of the time constant for a given gauge and capillary combination, the regions of continuum, transition, and free molecule flow should be considered individually since the magnitude of the conductance, and as a result, the time constant is a function of the flow conditions predominating in the capillary tube. In the case of the continuum regime, the flow conditions are determined solely by molecule-molecule collisions with the magnitude of the conductance being a function of the pressure level as a result. For the transition regime, both molecule-molecule and molecule-wall collisions influence the flow. In the region of free molecular flow, where the capillary conductance has the smallest numerical value, the flow properties are determined solely by molecule-wall collisions.

In order to indicate the longest times required for an equilibrium condition to be established, in a capillary-gauge system, only the free molecular conductance will be considered in establishing the time constants. To demonstrate the large difference between the conductance values for continuum and free molecular flow, one need only consider the conductance for a tube of length 100 cm. and diameter of 1 cm. under both conditions as given by Dushman (8). For continuum flow, the conductance is 675 liters/sec at a pressure of 380 torr while for free molecular flow the conductance is only 0.122 liters/sec., using air as the working fluid. Since the time constant is inversely proportional to S, the smaller the conductance, the larger the time required for equilibrium will be. Thus the use of the free molecular conductance to determine the time constants will yield the longest times required for equilibrium.

The free molecular conductance may be obtained from the relation given by Dushman in the form:

$$\frac{1}{S} = \left[\frac{2.39\,\ell}{d^3} + \frac{3.18}{d^2}\right]\left[\frac{M}{(83.1 \times 10^6)T}\right]^{\frac{1}{2}} \tag{4}$$

where d = tube diameter in cm

ℓ = tube length in cm

M = molecular weight of gas

T = temperature in $^{\circ}K$

S = conductance in cm^3/sec

Based on this value of the conductance and a standard gauge volume of one liter, Figures 9, 10 and 11 show the time required for the pressure in the gauge volume to drop to a value of 0.0498 of its original value for various lengths and diameters of connecting tubing when using helium, argon or nitrogen as the working gas at a gauge temperature of 300°K. The times obtained from these charts for a particular capillary are equivalent to three time constants for the particular tube.

The time constants for a given length and diameter tube, as selected from these figures, may be easily modified to reflect the change introduced by a gauge temperature other than 300°K or a gauge volume other than one liter. The value of the time constant, for a particular gas, is related to these quantities in the following manner:

$$\tau = V/S \sim V/T^{\frac{1}{2}} \tag{5}$$

Then, to adjust the values of the time constant for a gauge volume other than the standard one liter, the results obtained from the chart must be multiplied by the ratio of the actual gauge volume to the standard volume, or $\left[V(\text{actual-liters})/1\ \text{liter}\right]$. Similarly, to compensate for a difference in temperature, the square root of the ratio of the standard temperature to the actual gauge temperature, or $\left[300^{\circ}K/T(\text{actual})\right]^{\frac{1}{2}}$, must be used as the multiplying factor.

For a complete estimation of the time involved for a gauge-capillary combination to adjust to changing conditions, the cleanliness of the system must also be taken into account. This additional factor is required since, in the previous discussion, it was assumed that any outgassing effects were negligible. The effect of outgassing, which becomes more pronounced as the operating pressure of the capillary-gauge system is lowered, is to lengthen the time required for the pressure indicated by the sensor to change to a new value. The gas load that outgassing may impose on a given system is quite difficult to determine analytically. The material of which the system is constructed, the cleaning procedures employed, the length and conditions of any vacuum release, and the total surface area exposed to the vacuum are all parameters which may combine to govern the release of adsorbed gases into the system.

Rather than attempt to define a general method of predicting the effect of outgassing on the value of the time constant, one method is to use empirical service factors to adjust the time constant. In this approach, the time required for the gauge indication to change is multiplied by some numerical factor whose value depends upon the absolute pressure level of the system. Steinherz (9) has listed several service factors which were obtained from an analysis of the pump-down times of a number of mild steel vacuum systems. For system pressure levels between

1 torr and 1 x 10^{-1} torr, this factor is given as 1.5, while for pressures between 1 x 10^{-1} and 1 x 10^{-3} torr, it becomes 4. In the context of this analysis, the time values obtained from Figures 9, 10, and 11 must be multiplied by the appropriate factor for a given pressure level to obtain a more accurate estimation of the time.

As the system operating pressure is lowered below 1 x 10^{-1} torr the influence of outgassing becomes stronger with the result that the predictions of the response times for a given gauge-capillary system may be increasingly in error. In a system where pressures of this order and below are expected, initial considerations given to the selection of the capillary as well as operating techniques may be able to reduce the difficulties due to outgassing.

The dependence of the time constant on the capillary conductance requires that the conductance be large to attain short time constants. Thus, for a given capillary diameter, the length should be as short as possible to yield the maximum possible value of the conductance. This particular situation also gives the smallest surface area exposed to the vacuum and so limits the outgassing load. The initial outgassing from the capillary may also be reduced by the selection of a material, such as stainless steel, which has a low initial gas content. For low pressure operation, the outgassing load may be further reduced by providing a means of baking the system at an elevated temperature while under vacuum. For small systems, a temperature of 450°C applied for several hours is usually sufficient. Lower bakeout temperatures may be used, but the period of application of heat must then be longer.

After a system has been under vacuum and the surfaces have been degassed thoroughly, the method of vacuum release will greatly influence the outgassing load when the system is again under vacuum. The outgassing load after a vacuum release will be minimized if a dry gas is employed to back fill the system. Since water vapor is a major outgassing constituent in most small, unbaked systems, this technique will remove a large fraction of the outgassing load.

If an ionization gauge is used as the pressure sensor, an additional consideration is introduced which also requires that the outgassing be reduced. At a particular pressure, the output of an ionization gauge is a function of the gas that the gauge is immersed in. For example, when a gauge calibrated for nitrogen is used in a helium environment, the actual pressure will be approximately six times that indicated by the gauge. Thus, when a gauge calibrated for a particular gas is used, the wall outgassing must be reduced so that the gas composition will not be significantly altered causing errors in the evaluation of the system pressure. The use of an ionization gauge also requires that the effect of gauge pumping speed, relative to the value of the capillary conductance, be considered. If, in a particular system, the gauge pumping speed is large compared with the capillary conductance, the gauge volume may be pumped as a separate vessel and the pressure indicated by the gauge will bear little relation to the pressure existing at the system end of the capillary. Therefore, for proper operation under these conditions, the gauge pumping speed should be smaller, by at least a factor of ten, than the capillary conductance.

CONCLUSION

For any method of predicting the manner in which the thermal transpiration effect will alter the pressure indicated by a particular gauge-capillary combination, two important requirements are (1) a reasonable degree of accuracy and (2) the rapidity with which the required calculations may be carried out. As a result of a comparison with the present work, the use of Liang's equation to evaluate the thermal transpiration effect in tubes seems to be well justified. Edmonds and Hobson (1) have questioned the accuracy of Liang's equation in the pressure range where molecule-wall collisions begin to predominate in the respect that the orifice limit may not be reached in all cases for free molecular flow conditions as a result of imperfect molecular accommodation with the capillary walls. Although this fact will change the values of the transpiration ratio predicted by Liang's equation in a system near free molecular flow, the use of this relation with the orifice limit as a boundary value, rather than some modified form, is justified by the results of the present work. The near-attainment of the orifice limit for the stainless steel capillaries suggests that perfect molecular accommodation occurs in the capillaries. The diffuse reflection from the walls thus obtained yield equal transmission probabilities from either end of the capillary allowing the orifice limit to be reached.

For the engineer who must select a pressure measuring system, an important consideration may be the time required for the capillary-gauge combination to adjust to changing conditions at one end of the capillary.

The choice of such a combination may be limited by the nature of the process being monitored. Figures 9, 10 and 11 indicate that in a system where a given pressure level may be maintained for a period of several miniutes, neither the length nor the diameter of the capillary is severely restricted if the pressure is high enough to prohibit a large amount of outgassing. When the pressure is below 1×10^{-1} torr, the increase in the time constant for a given capillary cannot be predicted accurately due to the uncertainty in the amount of outgassing that may occur. Since Steinherz (9) has indicated that the time constant may be increased by a factor of four for pressures between 1×10^{-1} and 1×10^{-3} torr and perhaps by an even larger factor for pressures below 1×10^{-3} torr, a system bakeout should be employed to minimize the outgassing effects when operating in these pressure regions.

In a tube where molecular flow conditions prevail, the presence of curves or bends has no effect on the molecular transmission through the tube if diffuse reflection occurs from the tube walls. Thus the suggestion of this work that the transmission probability through the capillary is the same from either end indicates that the capillary connecting the source to the sensor may be curved if required without affecting the capillary-sensor characteristics.

APPENDIX A

The Absolute Method of Measurement of the Thermal Transpiration Ratio

In the absolute method, rather than directly measuring the pressure ratio existing between the capillary ends, it is calculated from measurements made at only one end of the capillary. The experimental procedure in this method is to admit a quantity of gas to the system, which is usually maintained at a uniform temperature of 300°K, and determine the pressure in the system after an equilibrium condition has been reached. Some volume of the system is then cooled to a new temperature and, after equilibrium has again been reached, the pressure is measured by the original gauge still maintained at 300°K.

In order to determine the pressure ratio from these measurements, it is assumed that the total mass of gas in the system is conserved in the gaseous phase during the cooling process. With this assumption, an expression of the equality of mass between the warm and cool states allows the pressure ratio to be found by the relation:

$$\frac{P_c}{P_h} = \frac{T_c}{T_h}\left[(1 + \frac{V_2}{V_1})(\frac{P_h'}{P_h}) - \frac{V_2}{V_1}\right] \qquad (6)$$

where P_c = pressure at cooled end of capillary

P_h' = initial pressure with entire system warm

P_h = pressure indicated in warm volume after cooling has taken place

T_c = temperature to which a portion of the system is cooled

T_h = initial temperature of entire system

V_2 = volume of system maintained at T_h

V_1 = volume of system cooled to T_c

In order that the assumption of constant mass not be violated, the absolute method requires the use of a test gas that is not absorbed at the temperature to which the system is to be cooled. Precautions are also required to insure that the test gas is of high purity with no contaminants that may later be condensed out of the gas phase.

This method is also very susceptible to error that may be introduced by any gauge pumping that may occur when ionization gauges are used for low pressure measurements. Due to its dependence on the initial system conditions, the absolute method will yield a steadily increasing value of the pressure ratio, in the presence of any gauge pumping, due to a constantly decreasing value of P_h.

APPENDIX B

The Analysis of Transmission Probabilities by Edmonds and Hobson

Edmonds and Hobson (1) have presented a simple model to account for the deviation of their experimental results from the theoretically expected limit at low pressures. A typical system consisting of two volumes connected by a capillary is shown in Figure 12.

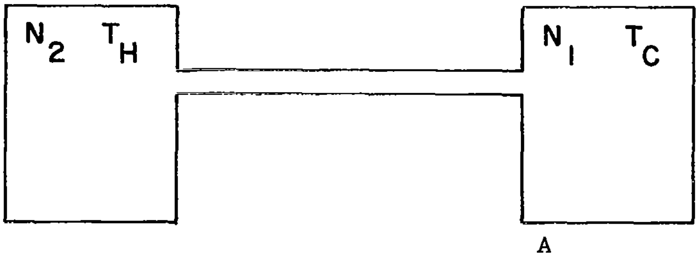

Figure 12. Model Used in Analyzing Capillary Transmission Probabilities

Assuming that a Maxwellian distribution exists in each vessel, the flux of particles to the capillary in volume 1 may be written as:

$$F_1 = \frac{n_1 v_1 A_1}{4} \tag{7}$$

where n_1 = number density in volume 1

v_1 = mean molecular speed in volume 1

A_1 = area of capillary

If it is assumed that a fraction, K, of the incident particles pass completely through the capillary, then a fraction (1 - K) return to the original volume. Thus, letting the condition of equilibrium be equal particle flux in each direction through the capillary, the net flux at plane A may be expressed as:

$$F_1 = K_h F_2 + (1 - K_c) F_1 \qquad (8)$$

This expression leads to the result that:

$$K_h F_2 = K_c F_1 \qquad (9)$$

Employing the relation for the particle flux and the ideal gas law, it follows that:

$$\frac{P_c}{P_h} = \left[\frac{K_h}{K_c}\right]\left[\frac{T_c}{T_h}\right]^{\frac{1}{2}} \qquad (10)$$

Since the limiting value of P_c/P_h was greater than $\sqrt{T_c/T_h}$ for the data of Edmonds and Hobson, the ratio of the transmission factors must be greater than unity. To account for this, the hypothesis was advanced that a molecule entering the capillary from the warm volume has a higher probability of transmission than one entering from the cold volume.

REFERENCES

1. Edmonds, T. and Hobson, J. P., "A Study of Thermal Transpiration using Ultrahigh Vacuum Techniques", Journal of Vacuum Science and Technology, Vol. 2, 1965, p. 182.

2. Hobson, J. P., "Surface Smoothness in Thermal Transpiration at very Low Pressures", Journal of Vacuum Science and Technology, Vol. 6, 1969, p. 257.

3. Liang, S. Chu, "On the Calculation of Thermal Transpiration", Journal of Physical Chemistry, Vol. 57, 1953, p. 910.

4. Smetana, F. O. and Daggerhart, J. A., Jr., "Pressure Sensitivity in Ionization Gauges", Journal of Vacuum Science and Technology, Vol. 5, 1967, p. 62.

5. Bennett, M. J. and Tompkins, F. C., "Thermal Transpiration: Application of Liang's Equation", Transactions of the Faraday Society, Vol. 53, 1957, p. 185.

6. Rosenberg, A. J. and Martel, C. S., "Thermal Transpiration of Gases at Low Pressures", Journal of Physical Chemistry, Vol. 62, 1958, p. 457.

7. Podgurski, H. H. and Davis, F. N., "Thermal Transpiration at Low Pressures: The Vapor Pressure of Xenon below 90°K", Journal of Physical Chemistry, Vol. 65, 1961, p. 1343.

8. Dushman, S., Scientific Foundations of Vacuum Technique, John Wiley and Sons, Inc., New York, 1962.

9. Steinherz, H. A., Handbook of High Vacuum Engineering, Reinhold Publishing Company, New York, 1963.

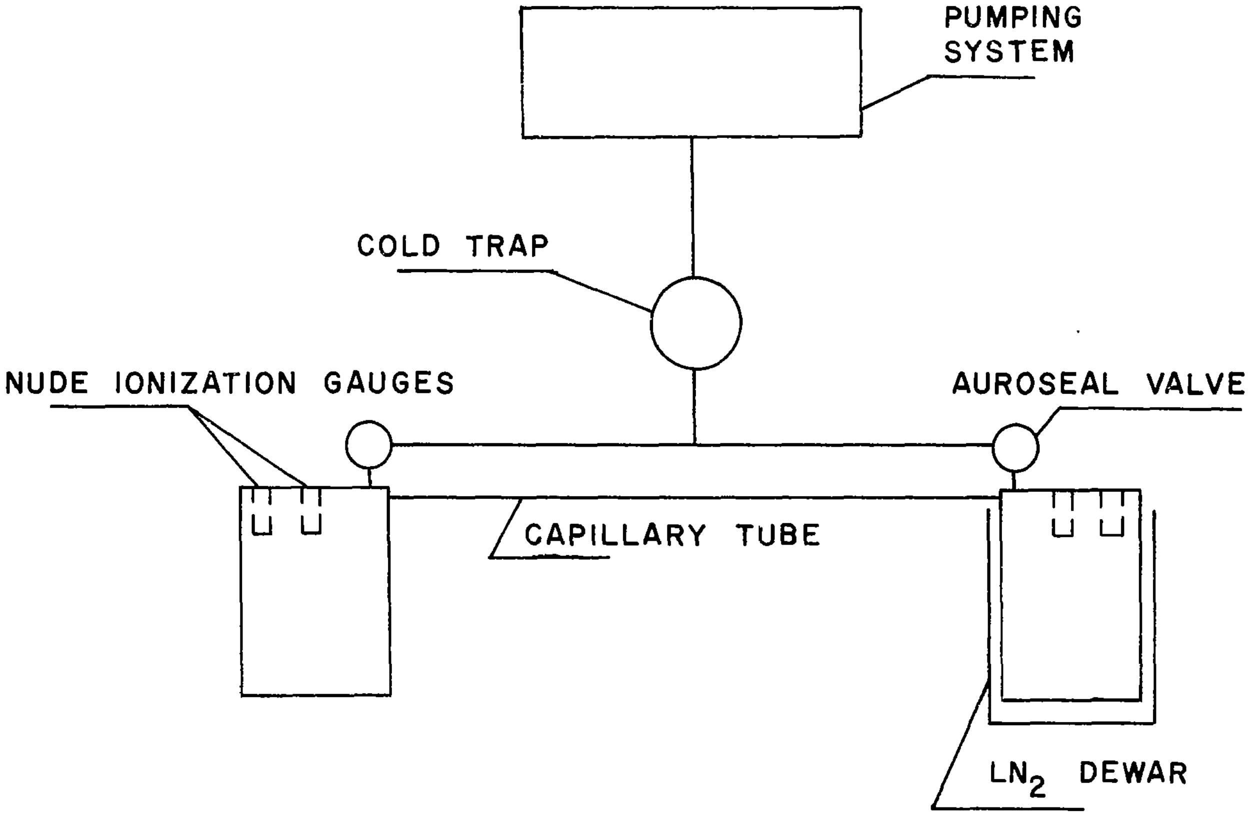

Figure 1. Schematic Diagram of the Experimental Apparatus

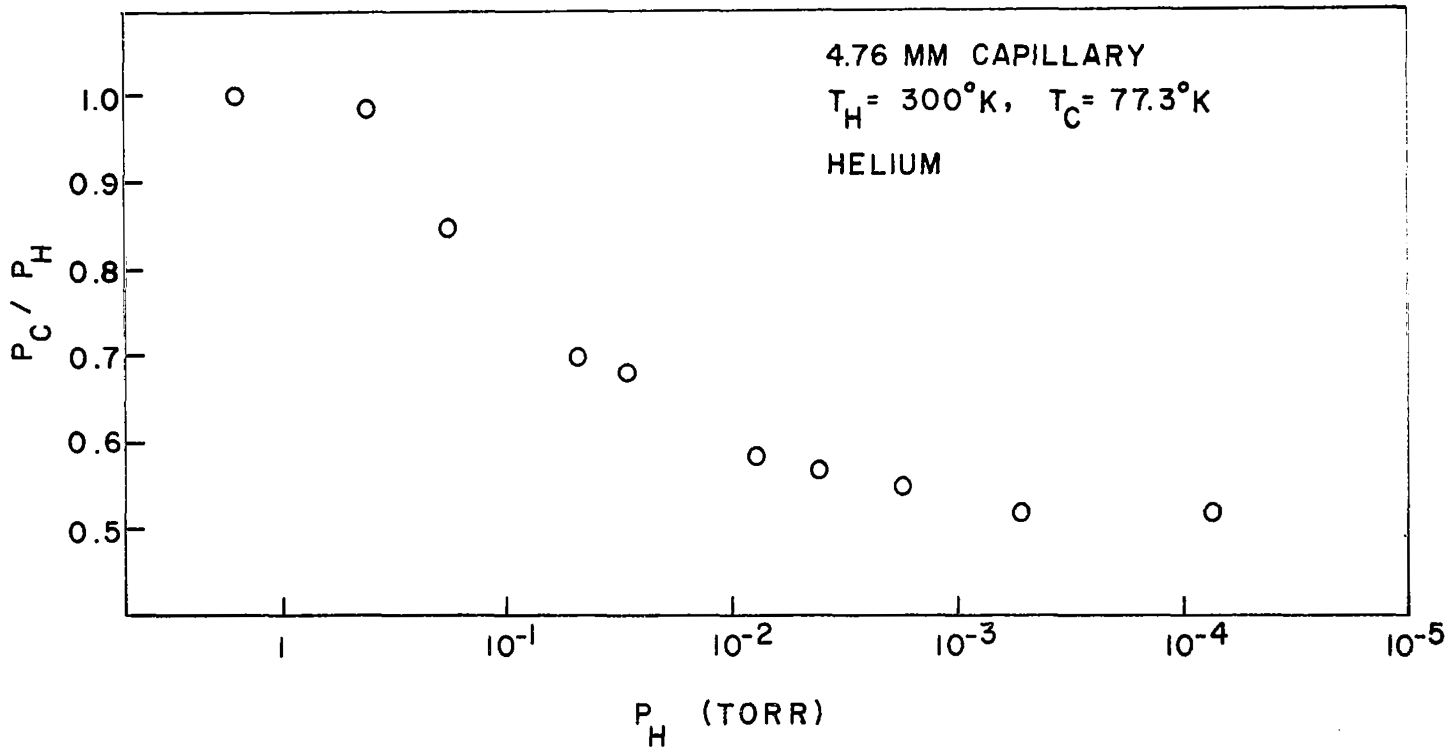

Figure 2. The Thermal Transpiration Effect for the 4.76 mm. Capillary

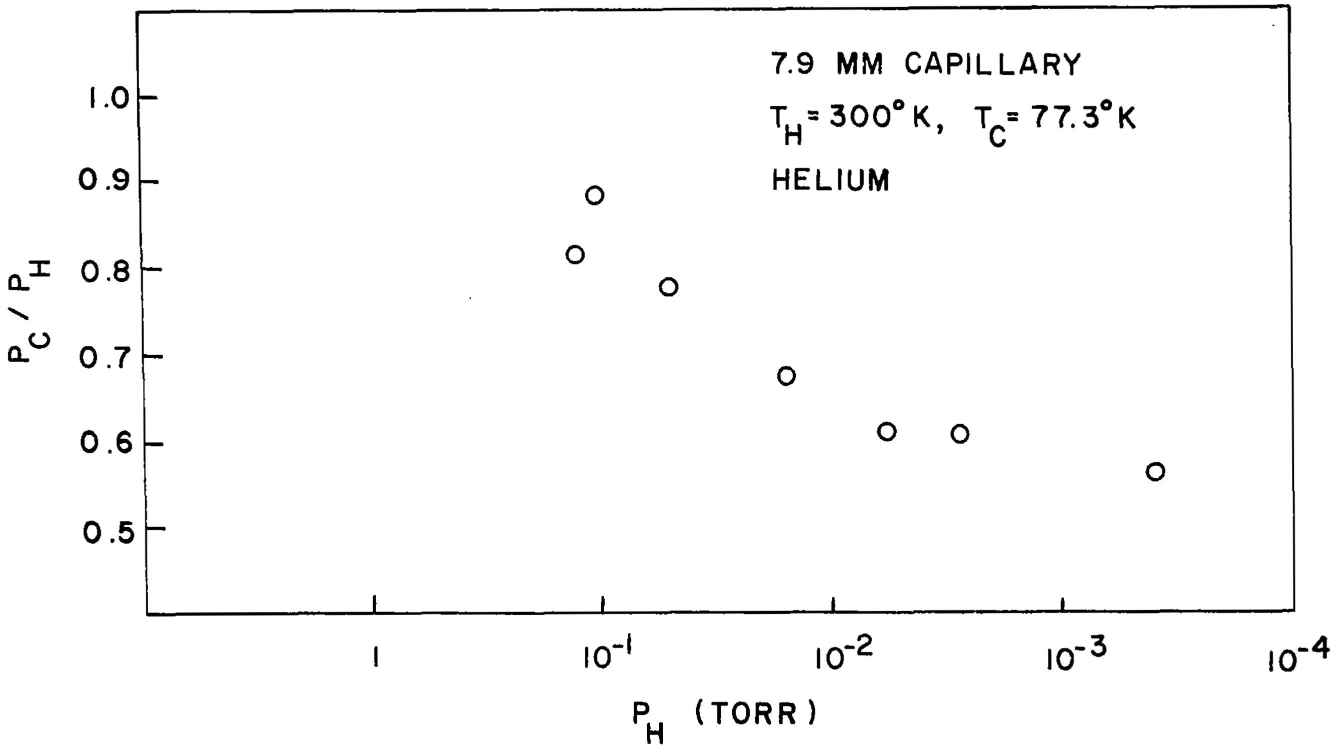

Figure 3. The Thermal Transpiration Effect for the 7.9 mm. Capillary

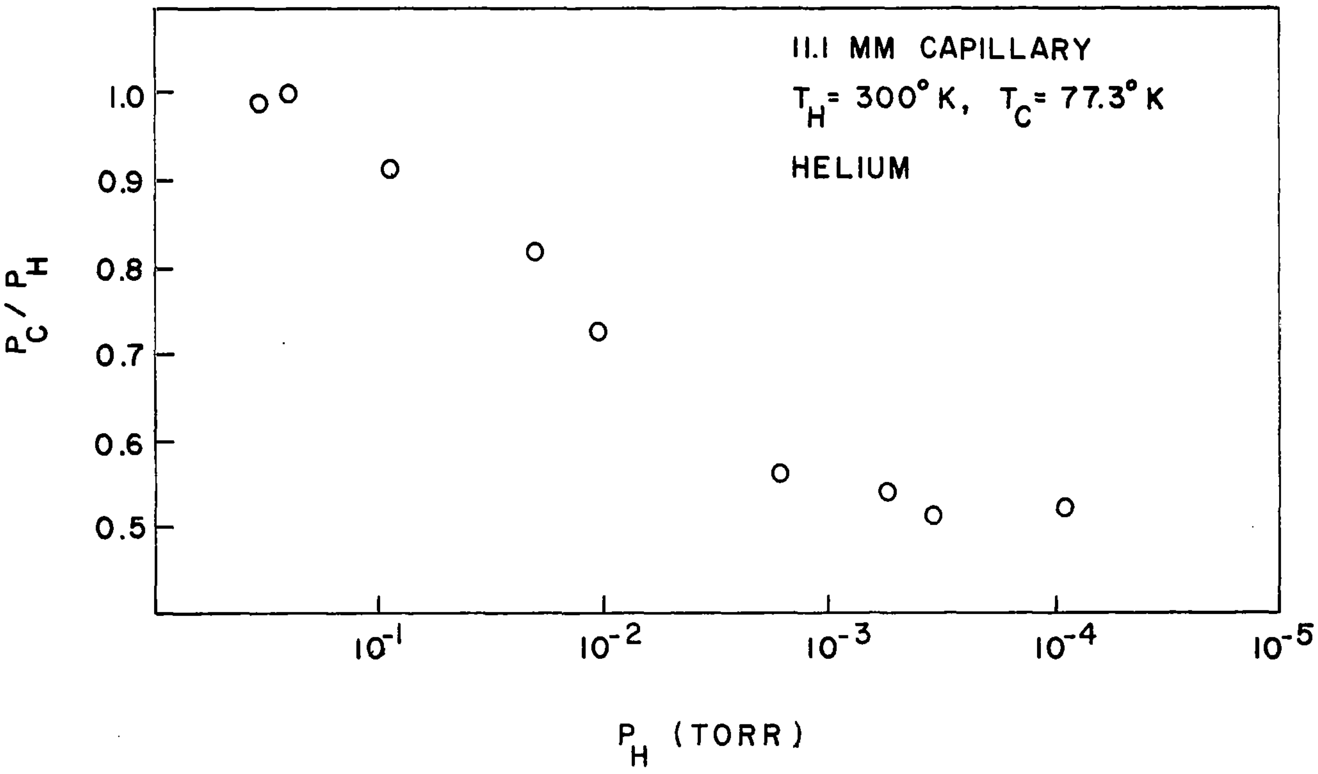

Figure 4. The Thermal Transpiration Effect for the 11.1 mm. Capillary

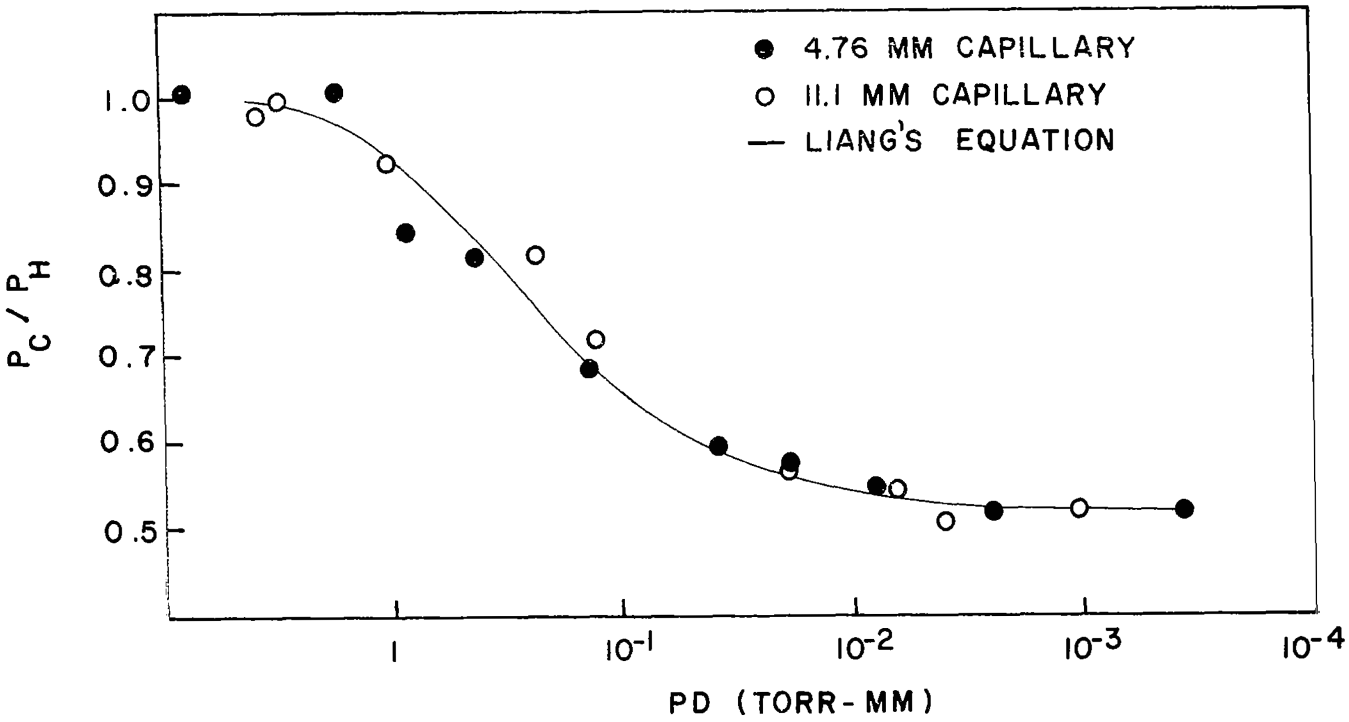

Figure 5. Comparison of Present Results with Liang's Empirical Equation

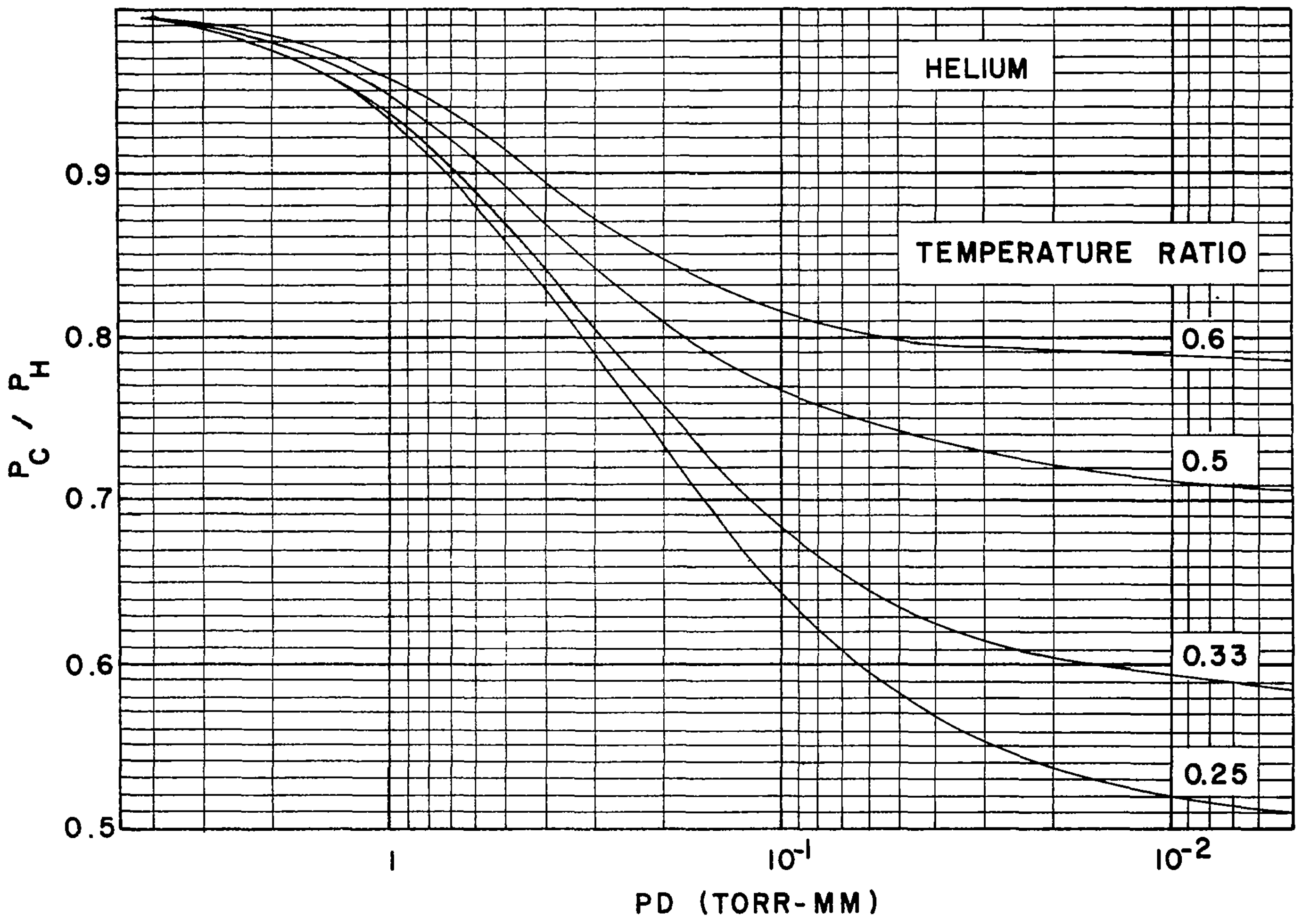

Figure 6. Thermal Transpiration Correction Chart for Capillary Tubes in a Helium Environment

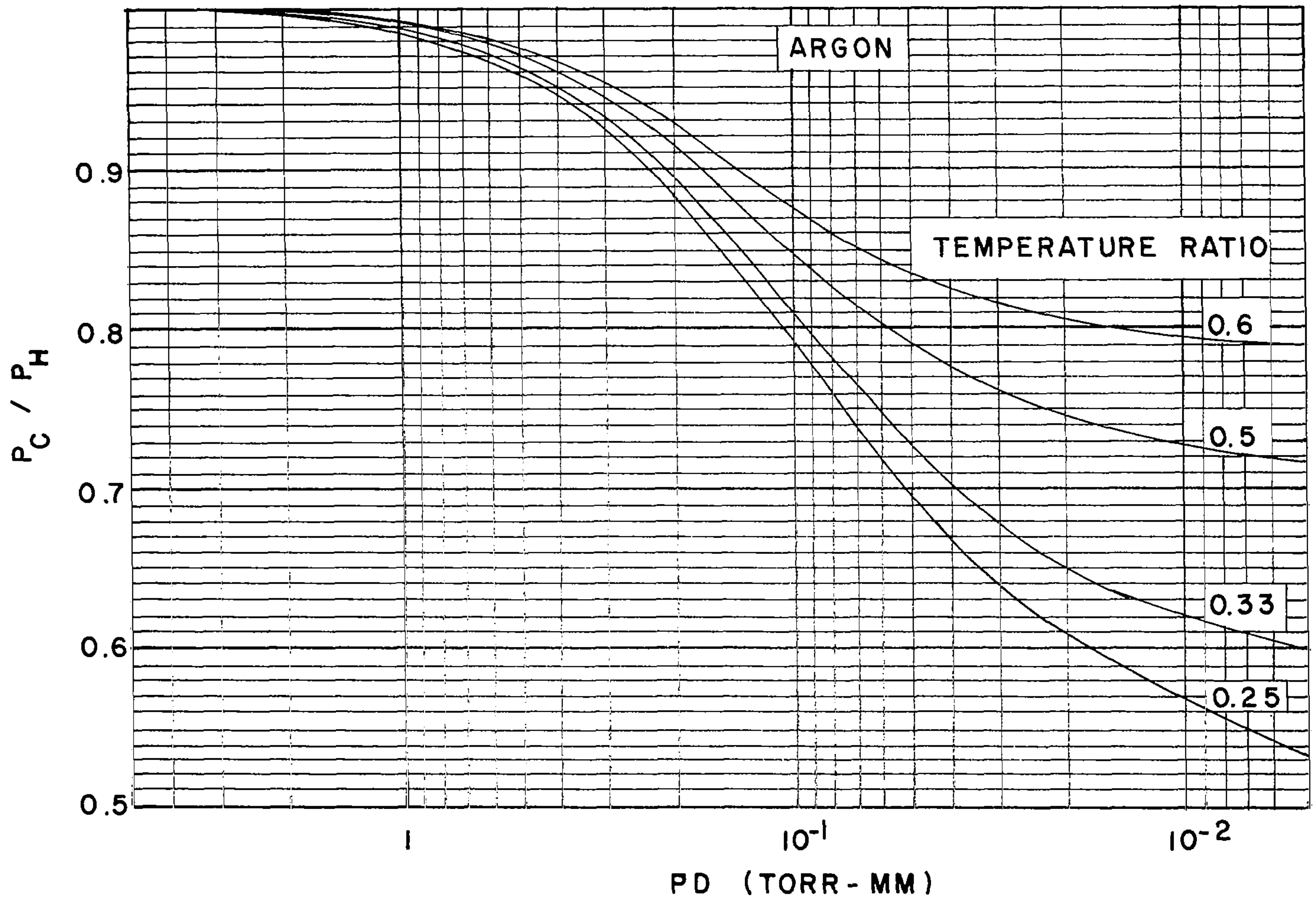

Figure 7. Thermal Transpiration Correction Chart for Capillary Tubes in an Argon Environment

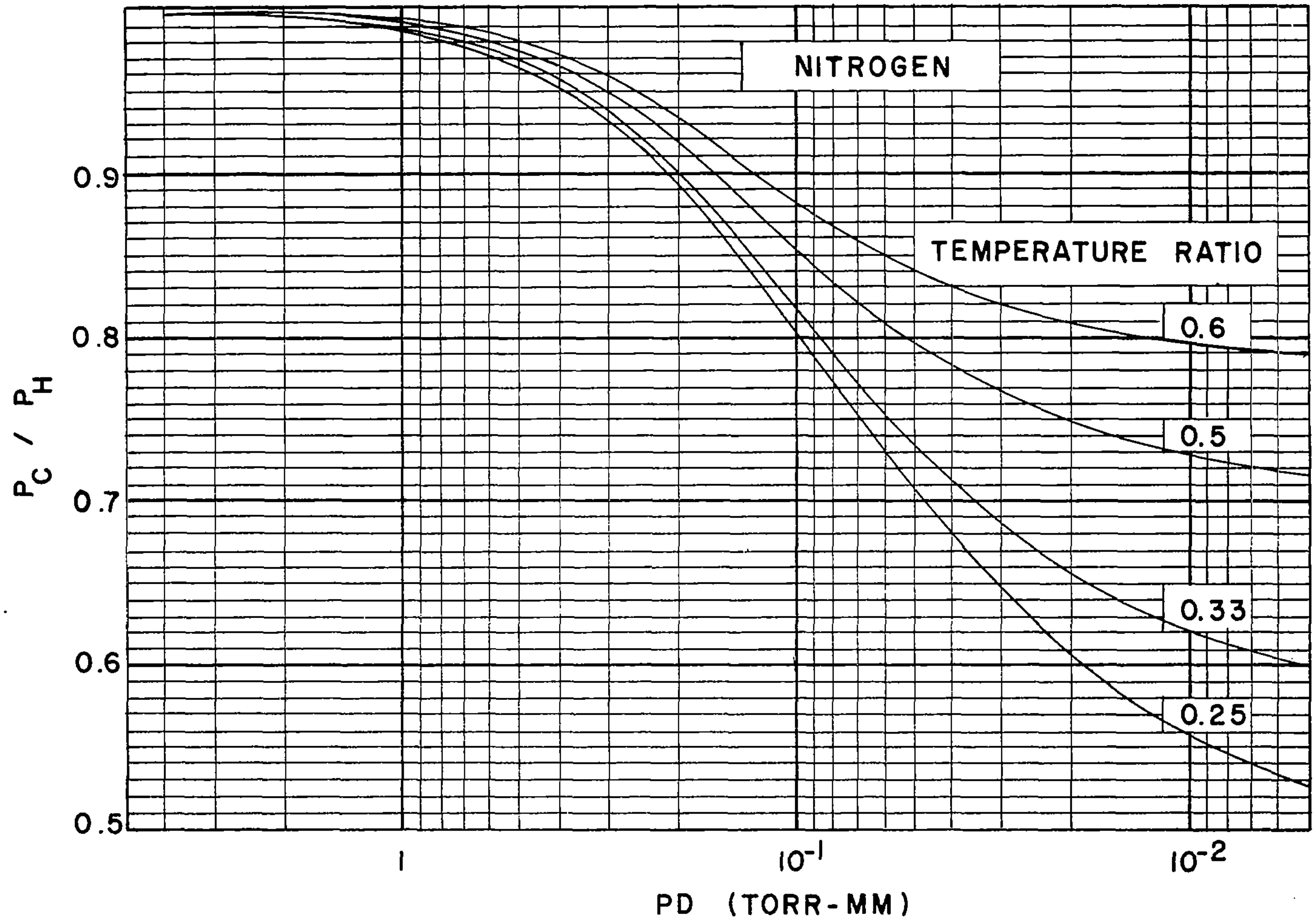

Figure 8. Thermal Transpiration Correction Chart for Capillary Tubes in a Nitrogen Environment

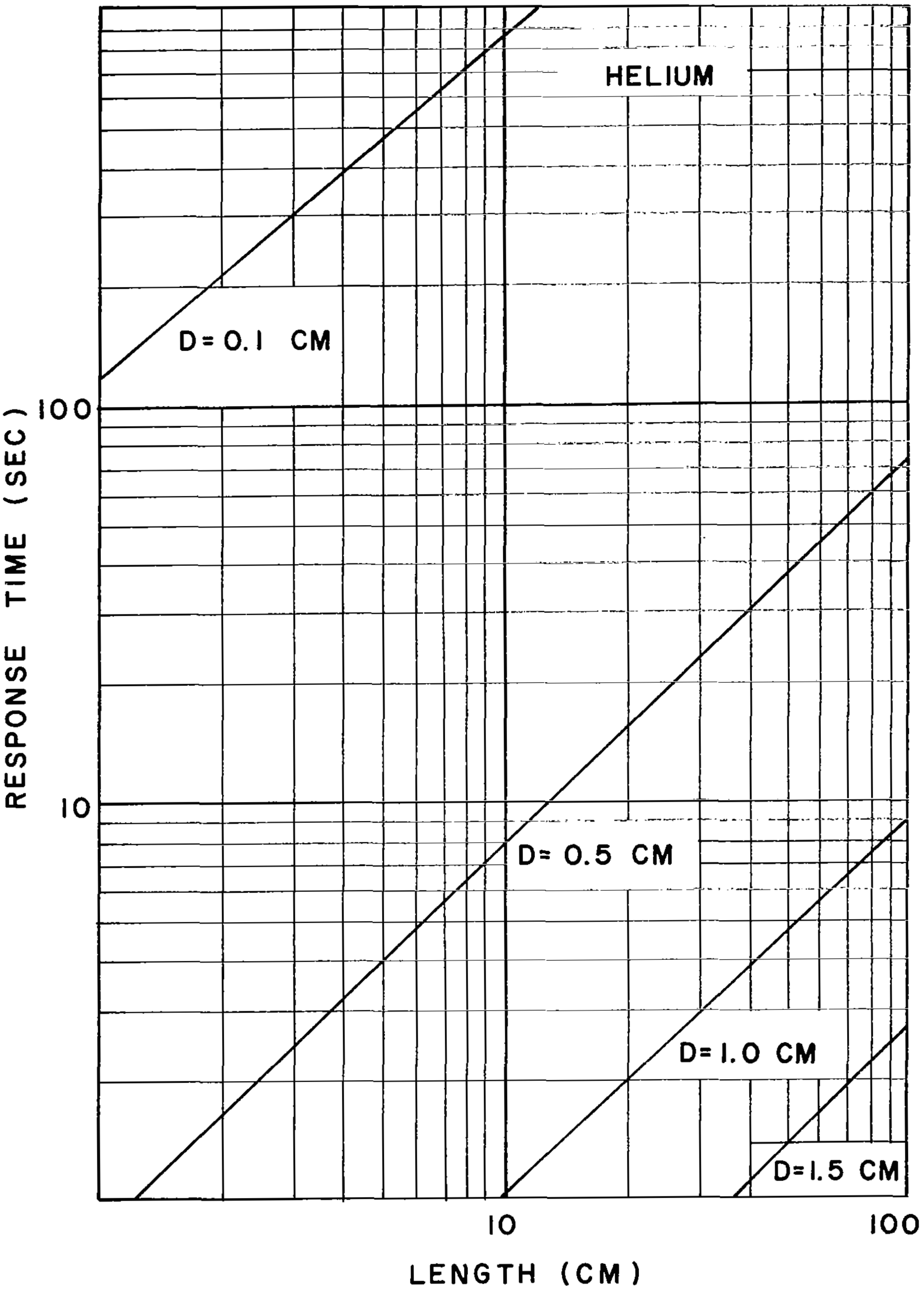

Figure 9. Capillary-Gauge Response Times in Helium

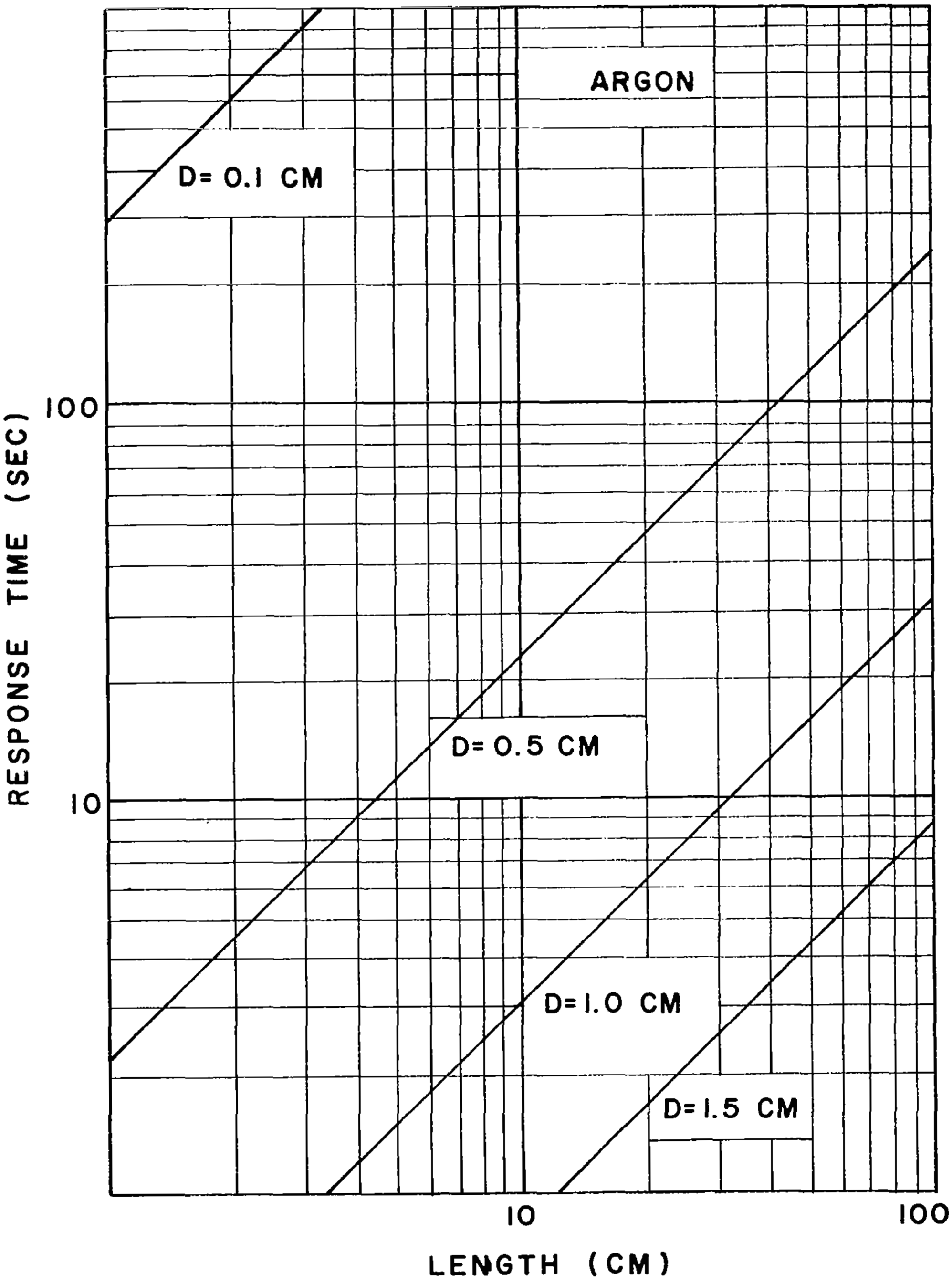

Figure 10. Capillary-Gauge Response Times in Argon

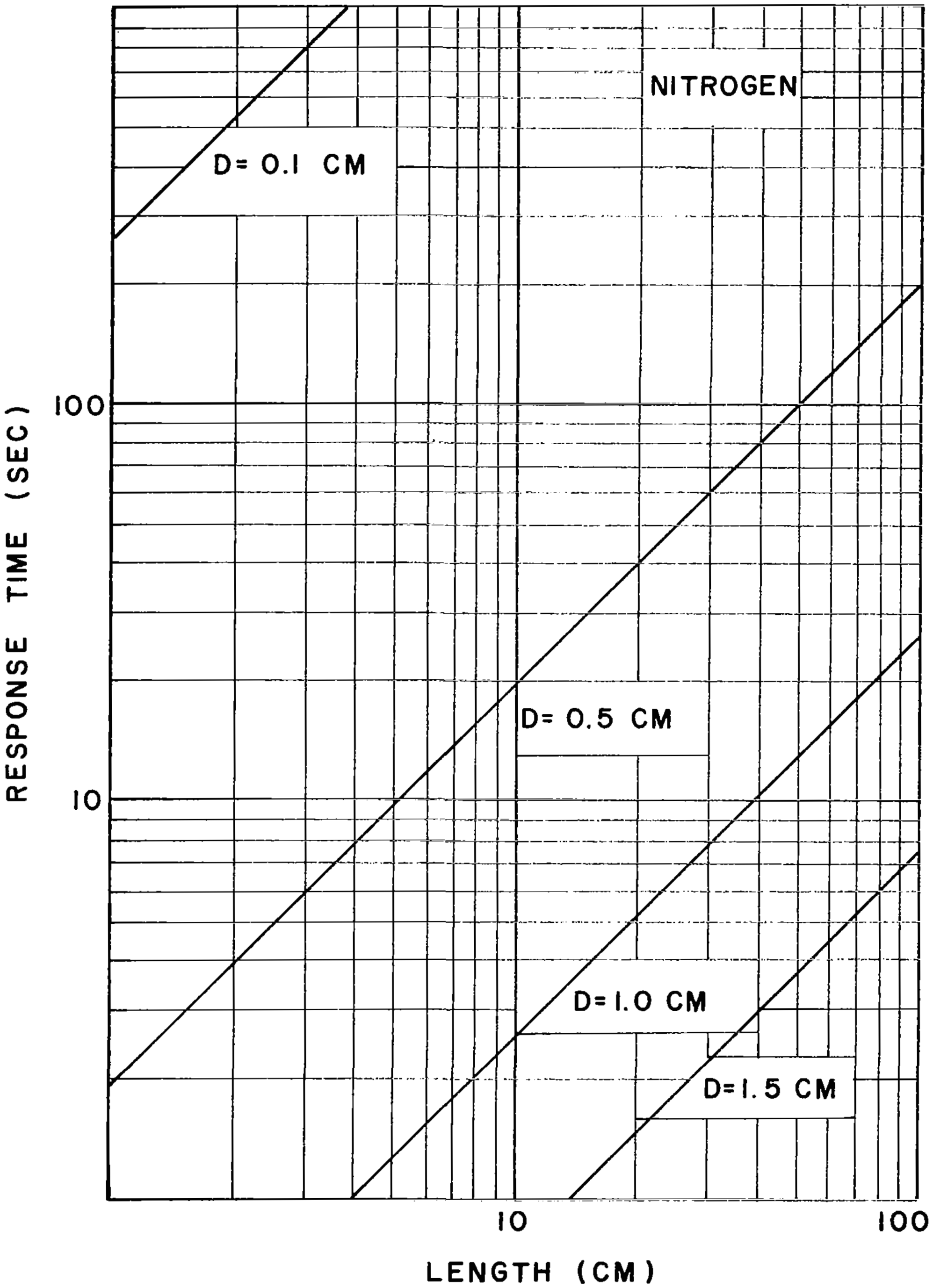

Figure 11. Capillary-Gauge Response Times in Nitrogen

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