CAPTURE COEFFICIENT OF 300°K CO₂ ON A
77°K SURFACE AS MEASURED BY THE
ROTATING GAGE TECHNIQUE

T. L. Moody
ARO, Inc.

January 1967

Distribution of this document is unlimited.

AEROSPACE ENVIRONMENTAL FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE
When U. S. Government drawings specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Documentation Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.
CAPTURE COEFFICIENT OF 300°K CO₂ ON
77°K SURFACE AS MEASURED BY THE
ROTATING GAGE TECHNIQUE

T. L. Moody
ARO, Inc.

Distribution of this document is unlimited.
FOREWORD

The research presented in this report was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65402234.

The research presented was conducted by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC under Contract AF 40(600)-1200. The research was conducted from December 1963 to December 1965, under ARO Project No. SW3417, and the manuscript was submitted for publication on October 25, 1966.

This technical report has been reviewed and is approved.

Terry L. Hershey  Edward R. Feicht
Captain, USAF  Colonel, USAF
Research Division  Director of Plans and Technology
Directorate of Plans and Technology
ABSTRACT

The capture coefficient of 300°K CO$_2$ on a 77°K surface is measured using a rotating gage measuring technique. It is concluded that the measured value is 0.99 ± 0.01. However, the experimental data also indicate that the radiation load on the cryosurface may significantly affect the capture coefficient.
CONTENTS

ABSTRACT ........................................ iii
NOMENCLATURE .................................. v
I. INTRODUCTION ................................... 1
II. EXPERIMENTAL METHOD ...................... 1
III. APPARATUS ................................... 4
IV. PROCEDURE ................................... 4
V. RESULTS AND DISCUSSION .................. 5
VI. COMPARISON OF RESULTS WITH OTHER
    INVESTIGATIONS ............................. 10
VII. CONCLUSION .................................. 12
REFERENCES ..................................... 13

TABLE

I. Radiation Loads ............................... 12

ILLUSTRATIONS

Figure
1. Vacuum System ............................... 1
2. Mass Spectrometer Ion Currents with
   Rotating Gage Inlet ........................ 5
3. Maximum Error in Eq. (1) Caused by Multiple
   Collisions .................................. 7
4. Error in Capture Coefficient for a 10-percent
   Error in Slope ................................ 9
5. Arrangement of Hemisphere and Supplementary
   Radiation Source ............................ 11

NOMENCLATURE

a  Area of gage opening, cm²
C  Capture coefficient
\( \frac{dn}{dt} \) Gas flux, molecules/sec

\( \frac{dn}{dt} \) \(_i\) Impinging gas flux, molecules/sec

\( \frac{dn}{dt} \) \(_r\) Rebounding gas flux, molecules/sec

\( I \) Ion current

\( I_i \) Ion current produced by impinging gas molecules

\( I_r \) Ion current produced by rebounding gas molecules

\( K \) Constant

\( M \) Molecular weight, gm/gm-mole

\( N_o \) Avogadro's number

\( P_i \) Pressure by gage facing away from hemisphere

\( P_r \) Pressure by gage facing toward hemisphere

\( R \) Universal gas constant

\( T \) Gas temperature, °K

\( \alpha \) Fraction of molecules removed by the gage

\( \beta \) Slope of Eq. (6)

\( \delta \) Error in capture coefficient caused by multiple collisions
SECTION I
INTRODUCTION

The capture coefficient of 300°K CO₂ on a 77°K surface has been reported in previous works (Refs. 1 through 6); however, the capture coefficients of these experiments have varied between 0.5 and 1.0.

This work was initiated in an attempt to make an independent measurement by using a different experimental technique. The method employed was used previously to measure the capture coefficient of H₂ gas on a titanium surface and was referred to as the rotating gage technique (Ref. 7). It was found to avoid many of the experimental difficulties encountered by earlier experimental methods.

SECTION II
EXPERIMENTAL METHOD

Consider a concave hemispherical pumping surface with a capture coefficient C (Fig. 1) and a uniform gas flux \( \frac{dn}{dt} \) impinging on the entrance plane. Situated in the entrance plane of the concave hemisphere is a pressure sensing device, such as a mass spectrometer, which can be rotated toward and away from the pumping surface.

Fig. 1 Vacuum System
If it is assumed that:

1. The gas entering the hemisphere is uniformly distributed across the entrance plane of the hemisphere,
2. The capture coefficient of the gas molecules not removed by one collision is unchanged by subsequent collisions with the pumping surface, and
3. The ion current produced in the mass spectrometer is directly proportional to the pressure.

Then it was shown (Ref. 7) that:

1. The gas flux emitted from the hemisphere \( \frac{dn}{dt} \) is uniformly distributed across the exit plane.
2. The ratio of pressures when the gage is rotated is

\[
\frac{P_r}{P_i} = \frac{1 - c}{1 + c}
\]

where \( P_i \) and \( P_r \) is the pressure produced in the mass spectrometer by the impinging and rebounding gas flux.

This method of measuring capture coefficients can be shown to have the following advantages.

1. It does not require a calibrated flow system and allows the measurement to be made at any desired pressure in the free molecular flow regime.
2. During the measurement, it is not necessary to isolate additional pumps from the chamber. As a result, these pumps can be used to prevent accumulation of noncondensable gases during the measurement.
3. The substrate area need not be known as long as the gage views only the substrate.
4. It is not necessary that the gage be calibrated, nor will a change in gage sensitivity affect the measurement if a linear gage is used.
5. The capture coefficient measurement is independent of gas temperature.

Although the rotating gage technique has several advantages, some experimental difficulties still exist.
It has been assumed that the gas flux to the hemisphere is uniformly distributed across the entrance plane. In practice, this ideal condition may require care to achieve, since the flux will be influenced by the cell's contents, location of gas source, and pump inlets. All of these things will contribute to nonuniformities in the flux.

Secondly, as a result of multiple collisions with the pumping surface, the gas temperature may change and therefore alter the capture coefficient. This would, of course, be contradictory to assumption 2. This will be discussed in more detail later. Further, Eq. (1) does not account for molecules which are re-evaporated from the pumping surface (those caused by the vapor pressure of the surface). It has also been derived on the assumption that the ion current produced in the pressure sensing device is directly proportional to the pressure. However, there is generally a nonzero indication experienced in such instruments, i.e., an ion current is measured even at zero pressure.

The ion current produced by the impinging pressure on a linear response pressure sensing device can be written

$$P_1 = K_1 I_i + K_2$$

where $K_2$ is the zero indication.

The pressure caused by the rebounding flux can be written in terms of the ion current as

$$P_r = K_1 I_r + K_3 + K_4 I_v$$

Where $I_v$ is the ion current produced by the molecules being re-evaporated from the surface. This current is assumed to be constant and independent of the impinging gas flux.

Equation (1) can now be written

$$\frac{K_1 I_r + K_3 + K_4 I_v}{K_1 I_i + K_2} = \frac{1 - C}{1 + C}$$

$$I_r = \left(\frac{1 - C}{1 + C}\right) I_i + \frac{1}{K_1} \left[ K_2 \left(\frac{1 - C}{1 + C}\right) - (K_3 + K_4 I_v) \right]$$

Since the last term on the right is a constant, Eq. (1) can be written

$$I_r = \left(\frac{1 - C}{1 + C}\right) I_i + K^i$$

If the experimental currents are now plotted, a straight line should result. The slope of this line will be equal to $\frac{1 - C}{1 + C}$. 
The above derivation also demonstrates why it is not necessary for the gage to be calibrated, since it is not necessary that the calibration constant \( K_1 \) be known.

SECTION III
APPARATUS

The vacuum system used in this study is shown in Fig. 1. This chamber is 2 ft in diameter and 3 ft long. Its pumping system is composed of a 6-in. oil diffusion pump backed by a mechanical forepump. The pumping system was separated from the chamber by a 6-in. sliding gate valve. A LN\(_2\) cold trap was located between the valve and diffusion pump.

The 5-in. radius hemispherical LN\(_2\) pumping surface was located as shown in Fig. 1 with the entrance plane in the center of the chamber.

The gas inlet consisted of a 1/4-in. stainless tube formed in a 5-in. diam ring. For gas to enter the cell, 80 20-mil holes were drilled in the top of the ring.

A mass spectrometer was mounted externally to the chamber with a 1-in. diam tube penetrating the chamber to the entrance plane of the hemisphere. The tube could be rotated by means of a rotating feed-through, located in the end flange.

SECTION IV
PROCEDURE

Each experimental run began by pumping the cell to a pressure in the \( 10^{-7} \) torr region by means of the diffusion pumps. The hemisphere was then cooled by passing LN\(_2\) through the coils. Carbon dioxide gas was next admitted to the cell through the gas addition system. The hemisphere was then precoated with a CO\(_2\) cryodeposit at a cell pressure of approximately \( 10^{-5} \) for a period of 2 hr. This resulted in a deposit thickness of about 30,000 monolayers. Next, the leak rate into the chamber was adjusted to result in a cell pressure in the \( 10^{-5} \) or \( 10^{-6} \) torr region.

The partial pressure analyzer tubulation was rotated so as to view away from the hemisphere, and the readings were recorded. The tubulation was then rotated 180 deg so as to view into the hemisphere, and the reading was again recorded. The gas leak rate was then adjusted to give a different gas flux to the pumping surface and the same procedure repeated.
SECTION V
RESULTS AND DISCUSSION

The ion current in the mass spectrometer produced by the gas flux entering and leaving the hemisphere is shown in Fig. 2. A straight line has been fitted to this curve by the method of least squares. From Eq. (6), the slope of this line should be equal to \( \frac{1 - C}{1 + C} \). From Fig. 2, the slope is found to be 0.0035 with a standard deviation of 0.00073. This results in a capture coefficient of from 0.996 to 0.997.

![Fig. 2 Mass Spectrometer Ion Currents with Rotating Gage Inlet](image)

4.1 ERROR ANALYSIS

4.1.1 Nonuniform Flux

If the gas flux entering the hemisphere is not uniformly distributed, an error will result, since this was a necessary assumption in deriving Eq. (1). To determine if any nonuniformities existed, the entrance tube of the mass spectrometer was moved across the entrance plane of the hemisphere, both while facing in and out of the hemisphere. No variation in reading was detected.

4.1.2 Capture Coefficient, Change Caused by Multiple Collisions

It is shown (Ref. 7) that Eq. (1) can be written in the form

\[
P_r = P_i \left[ (1 - C_1)^{0.5} + (1 - C_2)^2 (0.5)^2 + (1 - C_3)^3 (0.5)^3 + \ldots + (1 - C_6)^m (0.5)^m \right]
\]  (7)
The first term is the pressure produced in the gage by the molecules that have had one collision with the wall. The second term is the pressure produced by molecules which have had two collisions, etc. Since the capture coefficient is probably a function of gas temperature, the molecules which make more than one collision with the surface will have a different temperature and thereby a different capture coefficient from those which strike the surface only once. This will, of course, produce an error in Eq. (1). The worst possible case is when the accommodation coefficient is sufficiently large, so that the capture coefficient is one, for the molecules which make two collisions.

This maximum error, as a result of condensation on the second strike, is the difference between the two expressions

\[
\frac{P_2}{P_1} = \frac{1 - C_1}{1 + C_1} \quad \text{for } C = \text{constant} \tag{8}
\]

\[
\frac{P_2}{P_1} = \frac{1 - C_2}{2} \quad \text{for } C = 1.0 \text{ on second collision} \tag{9}
\]

Equating Eqs. (8) and (9), and solving for \(C_2\) in terms of \(C_1\),

\[
C_2 = \frac{3C_1 - 1}{1 + C_1} \tag{10}
\]

The error \(\delta\) will be

\[
\delta = \frac{C_2 - C_1}{C_2} \tag{11}
\]

Substituting for \(C_2\) from Eq. (10) gives

\[
\delta = \frac{C_2 - C_1}{C_2} = \frac{2C_1 - C_1 - 1}{3C_1 - 1} \tag{12}
\]

Equation (12) is shown graphically in Fig. 3. From this plot, the maximum possible error caused by a change in capture coefficient as a result of gas temperature change can be determined from the measured capture coefficient \(C_1\). It can be seen that if the measured capture coefficient is greater than 0.75, less than a 5-percent error will result. For smaller values, the error increases rapidly. Possible methods of handling this error are discussed in Ref. 7.

4.1.3 Gage Pumping or Cracking

The pumping of test gases by the pressure sensing devices may have an effect on the pumping speed or capture coefficient measurement. If a mass spectrometer is used, then the "cracking" of molecules has the same result as if the gas were pumped. With the rotating gage technique,
Fig. 3 Maximum Error in Eq. (1) Caused by Multiple Collisions

\[ \delta = \frac{C_2 - C_1}{C_2} \] (Reference Eq. (12))
the removal of test gas by the pressure sensing device will not affect the measurement if the removal rate is proportional to strike rate during the measurement. This can be seen as follows: If \( a \) is the fraction of the molecules \( \frac{dn}{dt} \) entering the gage that is removed, then the rate of removal \( \frac{dn}{dt}_p \) by the gage is

\[
\left( \frac{dn}{dt} \right)_p = a \left( \frac{dn}{dt} \right)_c
\]

(13)

The number flux indicated by the gage is then

\[
\left( \frac{dn}{dt} \right)_g = \left( \frac{dn}{dt} \right)_c - \left( \frac{dn}{dt} \right)_p
\]

(14)

\[
\left( \frac{dn}{dt} \right)_g = \left( \frac{dn}{dt} \right)_c (1 - a)
\]

(15)

This is the same effect as changing the gage sensitivity; however, since the gage sensitivity cancels out of the expression, the result is unchanged.

4.1.4 Sensitivity of Measurement

One method of determining the sensitivity of the measurement is to find the change in the capture coefficient that would result from a change in the slope from Eq. (6).

\[
\frac{dl_r}{dl_s} = \beta = \frac{1-C}{1+C}
\]

(16)

\[
C = \frac{1-\beta}{1+\beta}
\]

(17)

\[
dC = \frac{-2}{(1+\beta)^2} d\beta
\]

(18)

From Eqs. (17) and (18)

\[
\frac{dC}{C} = \frac{-2\beta}{1-\beta^2} \frac{d\beta}{\beta} = \frac{C^2-1}{2C} \frac{d\beta}{\beta}
\]

(19)

Equation (19) is shown graphically in Fig. 4 for a 10-percent error in measuring the slope. It can be seen that for large values of the capture coefficient, 0.9 or greater, that an error as large as 10 percent in the measured slope will only result in approximately a 1-percent error in measuring the capture coefficient.
Fig. 4 Error in Capture Coefficient for a 10-percent Error in Slope
From the sources of error considered in the preceding error analysis, it can be concluded that, since no appreciable error was incurred from (1) a nonuniform flux, (2) multiple collisions, or (3) gage pumping and since the slope could be measured to within 10 percent, then the value measured for the capture coefficient is within one percent for large capture coefficients, i.e., greater than 0.75.

SECTION VI
COMPARISON OF RESULTS WITH OTHER INVESTIGATIONS

Some of the variations in the reported value of capture coefficients (0.5 to 1.0) can be attributed to experimental errors, although it is unlikely that such large variations can be entirely a result of experimental error. However, some uncontrolled experimental variables may be the source of the observed differences.

One such parameter, suggested by Haygood (Ref. 8), might be the radiant heat load on the cryosurface. In this investigation, while the gas temperature was 300°K, only half of the radiation from the 300°K surface was incident on the cryosurface. The remaining radiation was emitted from a 77°K surface (self-radiation from the hemisphere).

A preliminary check of this hypothesis was made by adding to the heat load on the cryosurface. Since the experimental apparatus was not well adapted for this purpose, a systematic investigation was not attempted. However, the initial results indicated a significant effect, and further research appears to be warranted.

The object of the investigation was to supply sufficient radiation to the surface of the hemisphere to produce a radiant heat load equivalent to that on a convex cryosurface surrounded by a 300°K surface, with an emissivity of one. Such a surface receives about 0.05 w/cm². In this investigation, the surface was only receiving about 0.025 w/cm. It was necessary then to supply an additional 0.025 w/cm² uniformly on the hemisphere.

In order to accomplish this, a commercially available "point source," tungsten filament was located one radius below the entrance plane of the hemisphere (Fig. 5). The filament was then resistance heated to supply the necessary power to the filament corresponding to 0.025 w/cm² ±0.005 w/cm².

This amount of radiation, although small, was sufficient to reduce the capture coefficient approximately 15 percent. Such an effect might
Fig. 5  Arrangement of Hemisphere and Supplementary Radiation Source

easily explain the discrepancies in the data of previous investigations. Further, if this can be shown to be a general effect, that is, for other gases and cryosurface temperatures, then it might be expected to affect the design of future cryopumps as well as past cryopumping data. For example, Dawson (Ref. 6) has reported the effect of gas temperatures on the capture coefficient of CO₂ on a 77°K surface. These experiments were performed by maintaining a shroud around the cryosurface at the desired gas temperature and assuming that the test gas assumed the temperature of the shroud. It might be possible, however, that the different radiation loads from the shroud had a significant effect on the capture coefficient, rather than the gas temperature.
Table I shows the radiation load assuming an emissivity of one and measured capture coefficient for both Dawson's and this investigation. It should be noted that although the values of the capture coefficient at a radiation load of 0.05 W/cm$^2$ do not agree, Dawson's values did increase as the radiation load decreased. In fact, Freeman (Ref. 4) has reported that, using the same experimental chamber as Dawson, but a different experimental method, the capture coefficient of 300°K CO$_2$ surrounded by a 300°K surface is 0.82 to 0.85 which would be in good agreement with this work.

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Radiation Temperature, °K</th>
<th>Watts/cm$^2$ on Cryosurface Assuming an Emissivity of One</th>
<th>Capture Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moody</td>
<td>256</td>
<td>0.023</td>
<td>1.0</td>
</tr>
<tr>
<td>Moody</td>
<td>320*</td>
<td>0.060</td>
<td>0.85</td>
</tr>
<tr>
<td>Dawson</td>
<td>400</td>
<td>0.145</td>
<td>0.49</td>
</tr>
<tr>
<td>Dawson</td>
<td>300</td>
<td>0.046</td>
<td>0.64</td>
</tr>
<tr>
<td>Dawson</td>
<td>195</td>
<td>0.00817</td>
<td>0.80</td>
</tr>
<tr>
<td>Freeman</td>
<td>300</td>
<td>0.046</td>
<td>0.82 and 0.85</td>
</tr>
</tbody>
</table>

*Heated filament equivalent

SECTION VII
CONCLUSION

It is concluded that the capture coefficient for 300°K CO$_2$ on a 77°K surface is $0.99 \pm 0.01$ for the geometry used. The results of the cursory investigation of the effect of a small radiation load on the cryosurface indicated that the capture coefficient may be a strong function of the surrounding radiation. Such an effect could explain the discrepancies among previous investigators.
REFERENCES


4. Freeman, R. M. "An In-Chamber Vacuum Gage Calibration Method and Its Application to Cryopumping." To be published.


The capture coefficient of 300°K CO$_2$ on a 77°K surface is measured using a rotating gage measuring technique. It is concluded that the measured value is 0.99 ± 0.01. However, the experimental data also indicate that the radiation load on the cryosurface may significantly affect the capture coefficient.
carbon dioxide
rotating gage
cryosurface
radiation

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year, or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b. & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

   (1) "Qualified requesters may obtain copies of this report from DDC."
   (2) "Foreign announcement and dissemination of this report by DDC is not authorized."
   (3) "U.S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through                  ."
   (4) "U.S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through                  ."
   (5) "All distribution of this report is controlled. Qualified DDC users shall request through                  ."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.