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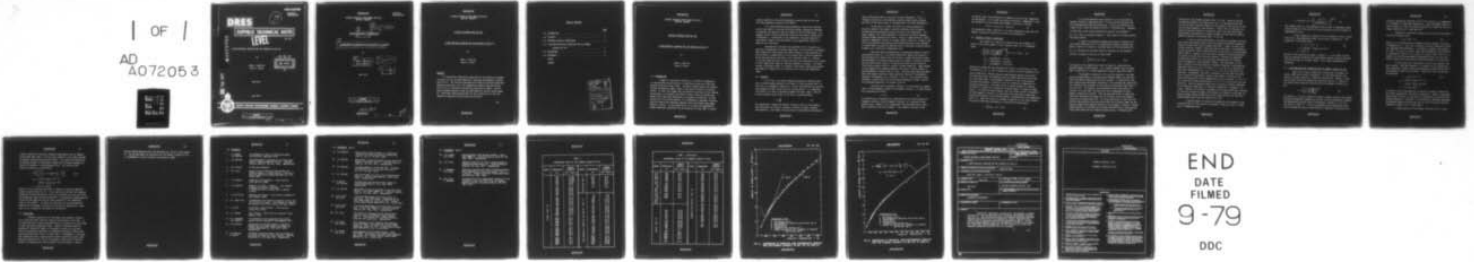
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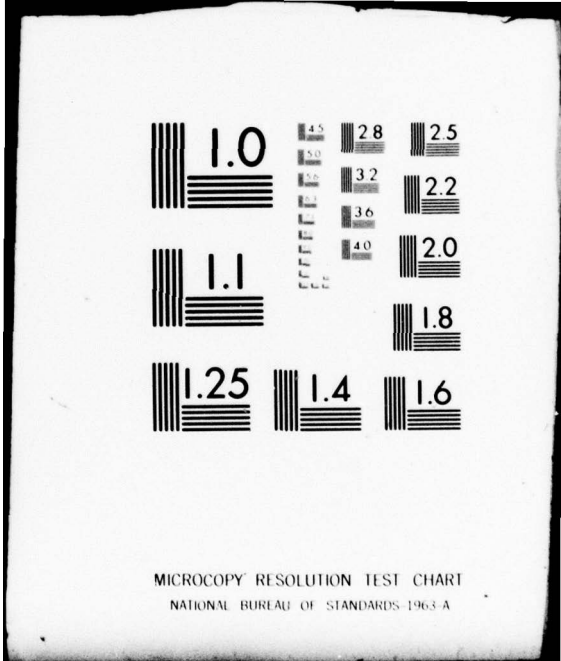
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A SEMI-EMPIRICAL EQUATION FOR THE VISCOSITY OF AIR (U)

by

James J. Gottlieb
David V. Ritzel

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A SEMI-EMPIRICAL EQUATION FOR THE VISCOSITY OF AIR (U)

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ABSTRACT

Sutherland's theoretical expression for the absolute or dynamic viscosity of a gas has been modified to represent experimental viscosity data for air. The resulting semi-empirical equation accurately describes measured viscosities of air for temperatures ranging from the boiling point at 78 K to molecular dissociating conditions at 2500 K. Discrepancies between measured values and semi-empirical results rarely exceed 2%. Other more limited expressions for the viscosity of air are also compared to measured viscosity data and discussed.

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1.0 INTRODUCTION

A means of specifying viscosity as a function of temperature is required when one analytically or numerically solves any fluid-flow problem involving viscous forces. Viscosity normally enters the analysis through the Reynolds number, which is the ratio of inertial to viscous forces. In turn, this number both characterizes the type of flow (laminar, transitional, or turbulent) and helps to select values of certain parameters such as the drag coefficient of an object or structure. For the solution of a fluid-flow problem, it is preferable to represent viscosity data by a simple and convenient equation, which facilitates easy computation of results. In the present work, it is shown that Sutherland's simple theoretical expression for the viscosity of a gas (Ref. 1) can be

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slightly modified to accurately represent viscosity data for air over the large temperature range of 78 to 2500 K.

It is worth mentioning that theoretical results for viscosity are not very useful in solving fluid-flow problems, because the equation or equations are generally much too complex to utilize effectively. For example, see the various expressions resulting from kinetic theory given in Reference 1. Furthermore, if any theoretical viscosity equation is sufficiently simple to use effectively in the computations, then it is generally too inaccurate.

Semi-empirical and empirical equations for air viscosity as a function of temperature are almost nonexistent in the scientific literature. Most researchers either choose the tedious method of using tabulated viscosity values in computations or do not report their viscosity equations. Of the few expressions available in the literature (Refs. 2, 3 and 4), it has been found that most of them are either too inaccurate or too limited in their temperature range for some new problems of interest. For these reasons, the present report is valuable in providing a simple and accurate semi-empirical equation for air viscosity over a very wide temperature range.

2.0 VISCOSITY

In all real fluid flows, momentum exchange and cohesion cause shear stresses between adjacent fluid layers in relative motion (Ref. 5). Viscosity is a fundamental property of a fluid, which defines the relationship between the shear stress and this relative motion. In a Newtonian fluid there is a linear relationship between the shear stress τ and the velocity gradient du/dy normal to the flow, as expressed below.

$$\tau = \mu \frac{du}{dy} \quad (1)$$

The coefficient μ denotes the dynamic viscosity, which is also known as the coefficient of viscosity, absolute viscosity or simply viscosity. From Equation 1, the dynamic viscosity may be interpreted as defining the

ratio of the shear stress to the rate of shear deformation. This is likened to the case in solid mechanics where the shear modulus defines the ratio of the shear stress to the magnitude of the shear deformation.

In the case of liquids, for which the viscous mechanism is primarily cohesion, the dynamic viscosity diminishes with increasing average molecular-separation distance and thus rising temperature. For gases, however, the viscous mechanism is principally molecular momentum exchange between adjacent fluid layers. Hence, a higher molecular kinetic energy or temperature results in a larger dynamic viscosity. Except in the case of an extremely high pressure which brings molecules closer together to significantly increase the cohesion effect, the dynamic viscosity may be assumed to be a function of temperature only.

There are several accepted ways of determining dynamic viscosity experimentally (Ref. 6). All devices essentially measure the stress or drag exerted by the laminar flow of the fluid. Common techniques include the measurement of torque exerted by coaxial cylinders in relative rotation when the small annular space is filled by the fluid, and the timing of fluid efflux through a hole in a vessel of known dimensions. Other methods use the damping of an immersed pendulum, the drag on a moving sphere, or the measurement of laminar flow in a duct. Viscosity data from such experiments with common fluids are readily available from most fluid-dynamics textbooks and handbooks (e.g., see Refs. 7 to 11). For convenient future reference, viscosity data for air have been reproduced in Table I and are also displayed graphically in Figures 1a and 1b.

Since the ratio of dynamic viscosity μ to fluid density ρ appears often in fluid-dynamics problems, the kinematic viscosity ν is often defined for convenience as follows:

$$\nu = \mu/\rho. \quad (2)$$

This definition is convenient for incompressible fluid flows because the kinematic viscosity, like the dynamic viscosity, is a function of temperature only. However, for a compressible flow the definition of kinematic viscosity is not very valuable. The kinematic viscosity is now

no longer a basic fluid property, but depends on both the gas temperature and the density. For an ideal gas having a pressure P , temperature T , and gas constant R , we can express the kinematic viscosity as follows:

$$\nu(T,P) = \mu(T)/\rho(T,P) = RT\mu(T)/P. \quad (3)$$

For compressible gases, therefore, it is most reasonable to deal with the dynamic viscosity and density as distinct fluid properties.

3.0 PREVIOUS VISCOSITY EXPRESSIONS

One example of an empirical expression for the kinematic viscosity of air, which appears in the literature (Ref. 2), is reproduced below.

$$\nu = \left[\frac{P_0}{P_a} \left(\frac{6 + P_s/P_a}{1 + 6P_s/P_a} \right) \left(\frac{P_s}{P} \right)^{0.714} \right] (b_0 + b_1T + b_2T^2) \quad (4)$$

$$b_0 = 9.027754 \times 10^{-5} \text{ ft}^2/\text{sec}$$

$$b_1 = -3.293413 \times 10^{-7} \text{ ft}^2/\text{sec}^\circ\text{R}$$

$$b_2 = 8.741066 \times 10^{-10} \text{ ft}^2/\text{sec}^\circ\text{R}^2$$

Because this expression was developed for a shock- or blast-wave air flow, the symbols P_0 , P_a , P_s , and P respectively denote sea-level atmospheric pressure (14.696 psia), ambient pressure, peak absolute pressure just behind the shock-wave front, and absolute pressure further behind the shock front or in the shock wave. The polynomial expression in the curved brackets describes the kinematic viscosity of air as a function of temperature at sea-level pressure P_0 . The other factor in square brackets is a density correction to account for the density variation owing to a pressure change from P_0 . It should be noted, however, that the correct version of Equation 4 for the kinematic viscosity in a shock-wave flow would have an additional multiplication factor in the square brackets, corresponding to the temperature ratio T_a/T . When this factor is included in Equation 4, the correct expression can be simplified considerably to yield the following result.

$$\nu = \frac{P_0}{P} (b_0 + b_1T + b_2T^2) \quad (5)$$

It is worth mentioning that Equation 5 is not restricted to problems involving a shock-wave flow. It can be derived directly from first principles and previous definitions. Firstly, by definition let ν equal $\mu(T)/\rho$, which also equals $RT\mu(T)/P$ or $(P_0/P)RT\mu(T)/P_0$. Secondly, let $RT\mu(T)/P_0$ in the latter expression be given by the polynomial $b_0 + b_1T + b_2T^2$, as defined originally. Then Equation 5 follows directly from these results.

In order to conveniently compare the results of Equation 5 or the original expression (Eq. 4) to experimental dynamic-viscosity data given in Table I or Figure 1a, the shock wave can first be omitted ($P_s = P_a = P$), and then the resulting identical equations can be expressed directly as dynamic viscosity, as given below.

$$\mu = \frac{P_0}{R} (b_0/T + b_1 + b_2T) \quad (6)$$

The results of this equation are shown in Figure 1a, along with the measured dynamic viscosity data. It is readily apparent that the agreement is good only in a limited temperature range of about 200 to 400 K.

The kinematic viscosity of air, given by Equation 4, has been used quite extensively in calculating the Reynolds number for shock and blast work done at DRES during the last ten years. A large part of this work involved the experimental evaluation of the unsteady drag coefficient for different sized cylinders in blast-wave and shock-tube flows (Refs. 2 and 12 to 21). For example, from the measured free-flight motion of a cylinder in a blast wave, the drag force can be determined by using Newton's second law of motion. Then the drag coefficient is simply the drag force divided by the product of the cylinder area and the dynamic pressure of the blast-wave flow. This drag coefficient is valid only for similar flow conditions characterized by both the flow Mach number and the Reynolds number which depends inversely on the kinematic viscosity. Another significant part of the DRES work involved the prediction of drag response from a blast-wave flow for shipboard antenna masts, a fiberglass whip

antenna and a UHF polemast antenna (Refs. 22 to 26). Based on the Mach and Reynolds numbers of the blast-wave flow, a corresponding drag coefficient for each structural element can be selected in the analysis to predict the drag response of the structure. Similar work on structural response to the drag loading of a blast wave, which uses drag coefficients experimentally evaluated for cylinders at DRES, has been done for DRES by Mechanics Research Incorporated (Refs. 27 and 28).

In all of the work mentioned in the previous paragraph, the blast waves under consideration were sufficiently weak that the peak temperature behind the shock front never exceeded about 400 K. Hence, in past calculations using the kinematic expression given by Equation 4, the temperature was not outside the range of applicability for the factor in curved brackets (200 to 400 K). However, since the correct kinematic-viscosity expression of Equation 5 should have been used, because it contains the additional multiplication factor T_a/T , the previously mentioned work is affected. The error depends on the blast-wave strength. The discrepancy in kinematic viscosity from using Equation 4 instead of Equation 5 containing the additional factor T_a/T can be as high as 2, 4, 10, 18, 25, 32 and 40% for peak shock overpressures ($P_s - P_a$) of 1, 2, 5, 10, 15, 20 and 25 psi respectively. Furthermore, the error in kinematic viscosity from using Equation 4 instead of experimental viscosity data (Table I), which are not represented accurately at high temperatures, can be as high as 1, 3, 10, 21, 32, 43 and 54% for peak overpressures of 1, 2, 5, 10, 15, 20 and 25 psi respectively. Such discrepancies would result in errors of similar magnitude for the Reynolds number which is inversely proportional to kinematic viscosity. However, the resulting discrepancy in the drag coefficient, selected on the basis of Reynolds number, would normally be smaller, except when the Reynolds number passes through the critical value defining the transition regime between subcritical and supercritical flow.

A second example of an empirical expression which appears in the literature (Ref. 3), this time for the dynamic viscosity of air in a shock wave, is reproduced below.

$$\mu = 0.21 \times 10^{-8} p_s^{0.214} \left[\frac{p_s^{0.715}}{0.247 \times 10^6 p_s T_s} \right]^{0.75} \quad (7)$$

This equation does not give meaningful results, even if reasonable assumptions are made as to the units for the two constants and the existence of typographical errors.

A final example of a dynamic-viscosity expression, which is applicable over a wide temperature range, can be found in Reference 4. This expression is reproduced below.

$$\mu = a T^{1.5} / (b + T) \quad (8)$$

$$a = 2.270 \times 10^{-8} \text{ slugs/ft sec } ^\circ R^{0.5}$$

$$b = 198.7 \text{ } ^\circ R$$

Results of this equation are shown in Figure 1a. It can readily be seen that this equation represents the experimental dynamic-viscosity data with little error from 78 K to about 1200 K. Such a good representation is noteworthy.

4.0 A NEW SEMI-EMPIRICAL EXPRESSION FOR THE DYNAMIC VISCOSITY OF AIR

Many of the rigorous theoretical formulations for dynamic viscosity, which can be found in Reference 1, are too complicated to use readily in either analytical or numerical calculations. However, a theoretical model originally proposed by Sutherland (see Ref. 1) results in the rather simple expression given below for the dynamic viscosity of a gas.

$$\mu = \mu_0 \left[\frac{1 + S/T_0}{1 + S/T} \right] \left[\frac{T}{T_0} \right]^{0.5} \quad (9)$$

The symbols μ_0 , T_0 and S respectively denote reference values of the dynamic viscosity and absolute temperature, and the so-called Sutherland's constant. The theoretically derived value of Sutherland's constant S is 113 K or 203 $^\circ R$ for air (Ref. 1). It must be pointed out that Sutherland's theoretical expression cannot be used directly in numerical or analytical cal-

culations, because the reference value of the viscosity μ_0 at temperature T_0 is unknown or unspecified theoretically. When experimental data are used to specify μ_0 , then the resulting expression of identical form is no longer theoretical but is semi-empirical.

Sutherland's theoretical expression can easily be rearranged to yield the following result,

$$\mu = a_0 T^{1.5} / (S + T), \quad (10)$$

where a_0 is a constant based on reference values of dynamic viscosity μ_0 and temperature T_0 . This form is identical to that of Equation 8, which was reproduced from Reference 4. In Equation 8, however, the constant b is 198.7 °R, which is slightly lower than Sutherland's value of 203 °R. If Sutherland's constant S is to retain its value of 203 °R or 113 K in Equation 10, then the experimentally determined value of a_0 will also differ slightly from the similarly determined constant a in Equation 8.

In the present work, Sutherland's value of the constant S has been retained. The other constant a_0 in Equation 10 was selected such that Sutherland's formula fitted the experimental viscosity data best in the temperature range of 100 to 800 K. Results for this case are summarized below.

$$\begin{aligned} \mu &= a_0 T^{1.5} / (T + S) & (11) \\ a_0 &= 1.47 \times 10^{-6} \text{ kg/m s K}^{0.5} \text{ or} \\ &7.35 \times 10^{-7} \text{ lb}_m/\text{ft sec } ^\circ\text{R}^{0.5} \\ S &= 113 \text{ K or } 203 \text{ } ^\circ\text{R} \end{aligned}$$

The results of this semi-empirical expression for dynamic viscosity do not differ substantially from those of Equation 8. Hence, if the results were plotted in Figure 1a, they would lie essentially on the solid line labelled Equation 8. Equation 11, like Equation 8, therefore represents the measured dynamic viscosity data for air with little error over the temperature range of 78 K to about 1200 K.

A simple equation for the dynamic viscosity of air is occa-

sionally required to accurately represent experimental data at temperatures higher than 1200 K. For this case, Equation 11 was simply extended by adding a suitable multiplication factor. This factor was selected by the authors because it conveniently reduced the differences between the results of Equation 11 and experimental data. The resulting semi-empirical expression is given below.

$$\mu = \frac{a_0 T^{1.5}}{T + S} \left[1.0 + 1.53 \times 10^{-4} \left(\frac{T}{S} - 1 \right)^2 \right] \quad (12)$$

$$a_0 = 1.47 \times 10^{-6} \text{ kg/m s K}^{0.5} \text{ or}$$

$$7.35 \times 10^{-7} \text{ lb}_m/\text{ft sec } ^\circ\text{R}^{0.5}$$

$$S = 113 \text{ K or } 203 \text{ }^\circ\text{R}$$

Results of this expression are shown in Figure 1b, along with measured dynamic-viscosity data for air. It can readily be seen that this equation represents the measured data not only very accurately, but also over twice the temperature range covered by Equation 8. Discrepancies between measured values and semi-empirical results rarely exceed 2% in the temperature range of 78 to 2500 K. It should be noted that this new semi-empirical equation for the dynamic viscosity as a function of temperature is quite easy to use in analytical and numerical calculations.

5.0 CONCLUSIONS

Different expressions for the dynamic and kinematic viscosity of air have been taken from the literature and assessed in this work. It was found that most of these expressions were too inaccurate or too limited in their applicable temperature range. However, expressions based on Sutherland's theoretical model of the dynamic viscosity of a gas were found to be generally successful in representing measured viscosity data from the boiling point of 78 K to about 1200 K. Furthermore, it was shown that Sutherland's basic equation could be easily modified to give a semi-empirical expression (Eq. 12) for the dynamic viscosity of air which represents the measured data very accurately from 78 to 2500 K. Discre-

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pancies between measured values and semi-empirical results rarely exceed 2%. The new semi-empirical expression for the dynamic viscosity of air is recommended for future viscosity calculations at DRES.

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TABLE I
EXPERIMENTAL VALUES OF THE DYNAMIC VISCOSITY OF AIR

SOURCE	TEMPERATURE (K)	DYNAMIC VISCOSITY (10^{-6} kg/m s)	SOURCE	TEMPERATURE (K)	DYNAMIC VISCOSITY (10^{-6} kg/m s)
Holman (Ref. 10)	100	6.924	Schlichting (Ref. 7)	223	14.6
	150	10.283		273	17.1
	200	13.289		323	19.6
	250	14.88		373	21.8
	300	18.46		473	25.9
	350	20.75		573	29.6
	400	22.86			
	450	24.85			
	500	26.71			
	550	28.48			
	600	30.18	CRC Handbook of Chemistry and Physics (Ref. 8)	79	5.51
	650	31.77		90	6.27
	700	33.32		169	11.30
	750	34.81		204	13.33
	800	36.25		242	15.39
	850	37.65		273	17.08
	900	38.99		291	18.27
	950	40.23		313	19.04
	1000	41.52		327	19.58
	1100	44.4		347	21.02
	1200	46.9		502	26.38
	1300	49.3		607	31.23
	1400	51.7		630	31.75
	1500	54.0		682	34.13
	1600	56.3		739	35.01
1700	58.5	754	35.83		
1800	60.7	810	36.86		
1900	62.9	838	37.50		
2000	65.0	893	39.16		
2100	67.2	911	40.14		
2200	69.3	1023	42.63		
2300	71.4	1083	44.19		
2400	73.5	1196	46.43		
2500	75.7	1307	49.06		
		1407	52.06		

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TABLE I (Continued)					
EXPERIMENTAL VALUES OF THE DYNAMIC VISCOSITY OF AIR					
SOURCE	TEMPERATURE (K)	DYNAMIC VISCOSITY (10^{-6} kg/m s)	SOURCE	TEMPERATURE (K)	DYNAMIC VISCOSITY (10^{-6} kg/m s)
Pofert and Svehla (CRC Handbook of Chemistry and Physics, Ref. 8)	300	18.4	Daugherty and Franzini (Ref. 8)	233	14.9
	400	22.7		244	15.6
	500	26.5		253	16.1
	600	29.9		255	16.2
	700	33.1		261	16.5
	800	36.2		266	16.8
	900	39.1		272	17.1
	1000	41.9		273	17.1
	1100	44.5		278	17.3
	1200	47.0		283	17.6
	1300	49.4		289	17.9
	1400	51.7		293	18.1
	1500	54.0		294	18.3
Kreith (Ref. 9)	256	16.52		300	18.4
	273	17.34		303	18.6
	311	19.12		305	18.7
	367	21.43		311	19.0
	422	23.96		313	19.0
	478	26.04		322	19.5
	533	28.13		333	19.9
	589	29.76		344	20.2
	644	31.80		353	20.9
	700	33.5		355	20.8
	756	35.1		366	21.5
	811	36.8		373	21.8
	1089	44.6		394	23.3
	1367	51.3		473	25.8
	1644	54.9			
	1922	57.6			

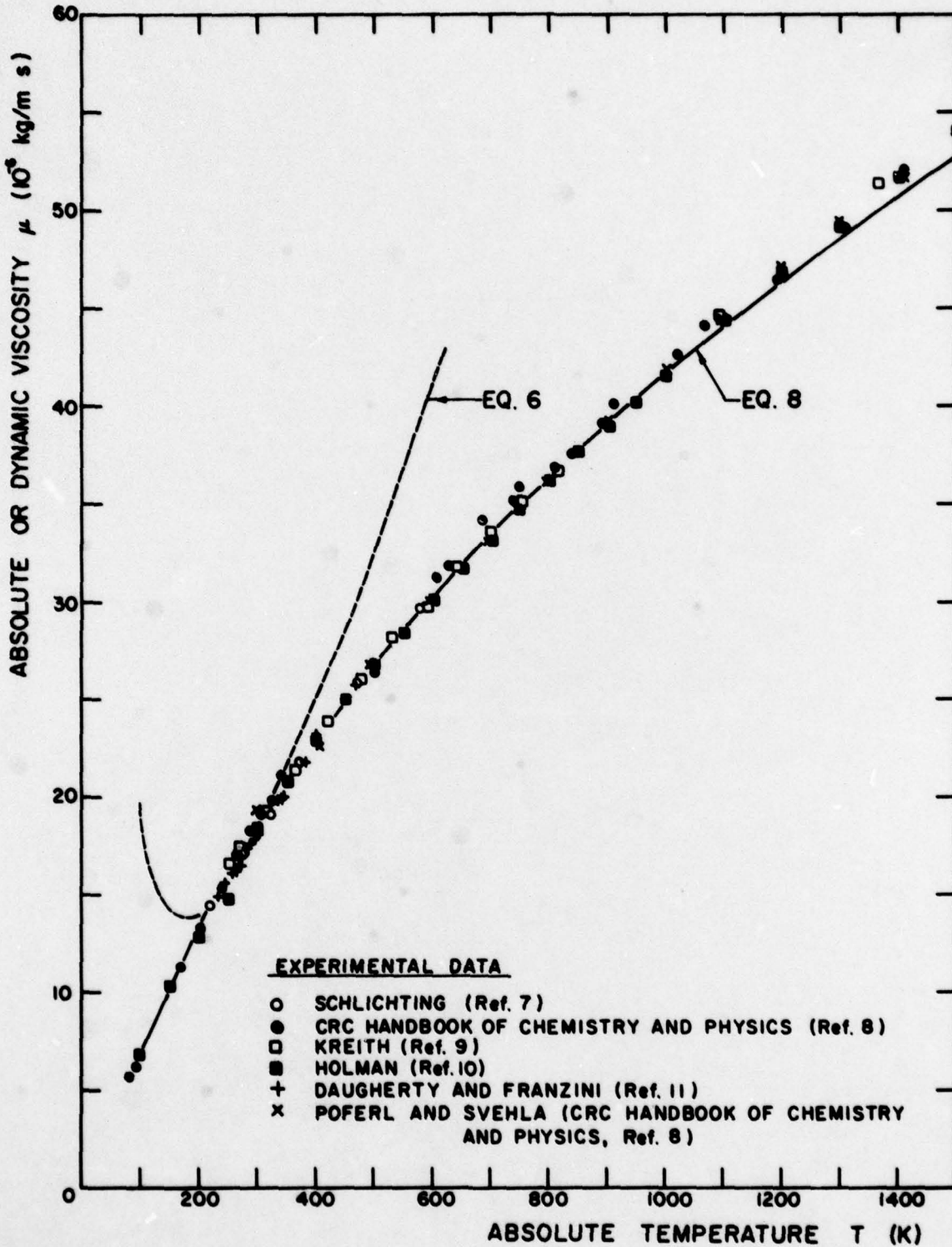


FIG. 1a. COMPARISON OF EMPIRICAL AND EXPERIMENTAL RESULTS FOR THE DYNAMIC VISCOSITY OF AIR (78 TO 1500 K).

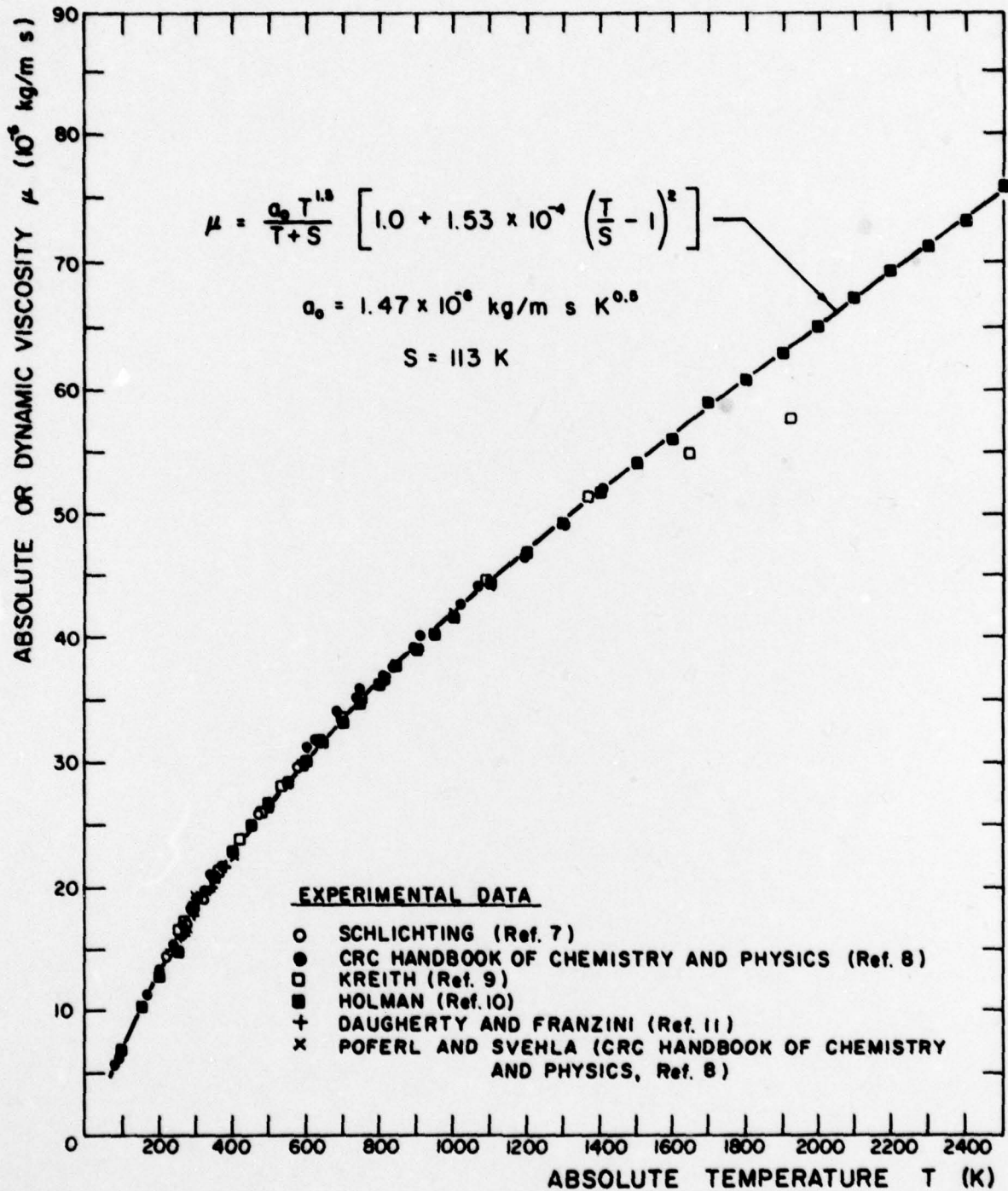


FIG 1b. COMPARISON OF EMPIRICAL AND EXPERIMENTAL RESULTS FOR THE DYNAMIC VISCOSITY OF AIR (78 TO 2500 K).

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13. ABSTRACT

Sutherland's theoretical expression for the absolute or dynamic viscosity of a gas has been modified to represent experimental viscosity data for air. The resulting semi-empirical equation accurately describes measured viscosities of air for temperatures ranging from the boiling point at 78 K to molecular dissociating conditions at 2500 K. Discrepancies between measured values and semi-empirical results rarely exceed 2%. Other more limited expressions for the viscosity of air are also compared to measured viscosity data and discussed.

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KEY WORDS

Dynamic Viscosity of Air
Kinematic Viscosity of Air

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