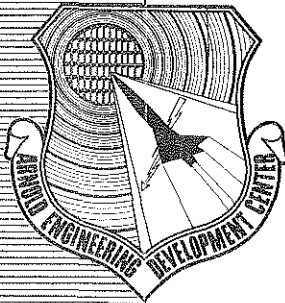


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SIMULATION OF HIGH TEMPERATURE AIR FOR AERODYNAMIC AND HEAT TRANSFER TEST PURPOSES

By

K. E. Tempelmeyer, M. H. Nesbitt, and J. E. Shepard
Propulsion Wind Tunnel Facility
ARO, Inc.

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ARO, Inc.,
a subsidiary of Sverdrup and Parcel, Inc.

March 1962

ARO Project No. 200937

FOREWORD

The authors would like to acknowledge the assistance of Mr. D. Baker of the Propulsion Wind Tunnel Facility, Propulsion Branch, who put the rather complex test apparatus into operation. Mr. Baker was also responsible for improving the efficiency of the combustor which made the experimental verification possible. Also, thanks are due to Mr. E. Anspach of the Research and Performance Branch who participated in the early phases of the experimental tests.

ABSTRACT

A method to simulate a gaseous test medium for aerodynamic and heat transfer test purposes is proposed. The solution of a set of simultaneous equations is employed to specify a gas mixture which has the same macroscopic thermal and transport properties as some other gas or mixture.

Experimental tests to determine the effectiveness of this gas simulation theory are also described. The addition of small amounts of argon, helium, and oxygen to a hydrocarbon combustion gas resulted in a new gas mixture which produced the same heat transfer and friction coefficients as air heated to the same temperature. A combustion gas test medium alone, however, exhibited different heat transfer characteristics than air. Thus, it appears possible to avoid the use of some impractical test medium for certain test purposes by replacing it with a more convenient mixture of gases.

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NOMENCLATURE

b	van der Waals correction factor for molecular volume, ft^3/mole
C. G.	Combustion gas
c_p	Specific heat at constant pressure, $\text{Btu}/\text{lb}_m\text{-}^\circ\text{R}$ or $\text{Btu}/\text{mole-}^\circ\text{R}$
c_v	Specific heat at constant volume, $\text{Btu}/\text{lb}_m\text{-}^\circ\text{R}$ or $\text{Btu}/\text{mole-}^\circ\text{R}$
D	Diameter, ft
D_s	Self-diffusion coefficient, ft^2/sec
$\bar{E}$	Average energy, Btu
f	Number of degrees of freedom or friction coefficient
f/a	Fuel-air ratio, $\text{lb}_m \text{ fuel}/\text{lb}_m \text{ air}$
G	Mass velocity, $\text{lb}_m/\text{ft}^2\text{-sec}$
h	Heat transfer coefficient, $\text{Btu}/\text{ft}^2\text{-sec-}^\circ\text{R}$
K	Gas thermal conductivity, $\text{Btu}/\text{sec-ft-}^\circ\text{R}$
k	Boltzmann's constant, $\text{Btu}/^\circ\text{R}$
L	Tube length, ft
M_∞	Mach number
MW	Molecular weight, lb_m/mole
m	Mass of molecule, lb_m
m_g	Gas mass flow rate, lb_m/sec
N	Number of molecules per ft^3
N_0	Avogadro number, particles/mole
p	Pressure, psfa or psia
R	Gas constant, $\text{ft-lb}_f/\text{lb}_m\text{-}^\circ\text{R}$
Re_D	Reynolds number based on tube diameter
S	Surface area of tube, ft^2
T	Temperature, $^\circ\text{R}$
V	Velocity, ft/sec

$\bar{v}$	Mean molecular velocity, ft/sec
x	Mole fraction
Z	Collision frequency, number/sec
γ	Specific heat ratio
Δ	Repeatability of parameter
Δp_{fr}	Tube frictional pressure loss, psf
ΔT	Combustor temperature rise, °R
δ	Repeatability of measurement
η_c	Combustion efficiency
λ	Mean free path, ft
μ	Gas viscosity, lb _m /ft-sec
ρ	Density, lb _m /ft ³
σ	Molecular collision cross section, Å ²
σ^*	Molecular radius, Å (1Å = 3.28 x 10 ⁻¹⁰ ft)
Ω	Absolute humidity, lb _m water/lb _m dry gas

SUBSCRIPTS

1, 2 . . n	Components
1	Entrance to tube
2	Exit from tube
air	Air
b	Average or bulk
e	Equilibrium
gas	Gas
m	Mixture or mass
stoic	Stoichiometric
t	Stagnation
v	Vapor
w	Wall

1.0 INTRODUCTION

High temperature air is required as a test medium for research and development testing in various fields and particularly in aerodynamics. However, it is not always convenient or possible to provide large mass flows of air with a sufficiently high energy level to fully simulate flight conditions. Similar instances arise where some undesirable characteristics of a particular gas or gas mixture hamper or restrict its use for test purposes.

A method is suggested in Ref. 1 in which a gas mixture may be specified which has the same macroscopic equilibrium and transport properties as some other gas or gas mixture. This theory is based on the concept that most gas dynamic and heat transfer phenomena in the temperature range of negligible dissociation depend upon the macroscopic or bulk properties of the test medium rather than upon its microscopic structure. Consequently, air at elevated temperatures could be simulated for gas dynamic test purposes by combustion gases, for example, if certain gases are added to the combustion products to alter their bulk properties to those of air. The use of combustion products to simulate air is convenient because high temperature combustion gases can be produced in large amounts. This technique is not limited to the simulation of air by combustion products, but also offers an interesting possibility for the simulation of other gases including other planetary atmospheres.

This report summarizes an analytical and experimental study of this simulation technique. The theory is briefly reviewed, and the results of experimental tests undertaken to determine the validity of this method are described. Previously published work relating to this study is contained in Refs. 1 through 3.

2.0 THEORY

The requirements necessary for two gases or gas mixtures to exhibit the same or nearly the same thermodynamic properties have been examined for the following conditions:

1. All gases obey the perfect gas equation of state, but the variable specific heats of the diatomic and polyatomic gases are taken into account.

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2. The pressure and temperature of the mixture may be adjusted to those of the gas it is to simulate:

$$P_{gas} = P_m ; \quad T_{gas} = T_m$$

3. The degree of dissociation is negligible at temperatures below 4000°R for all gases considered.
4. When combustion gases are employed, a combustion efficiency of 100 percent is assumed, and any water formed during combustion remains in the vapor state.

One approach to define a gas mixture with a given set of properties would be to specify a mixture equation for each property to be duplicated and then attempt to satisfy this group of equations simultaneously by variation of the mixture components and proportions. This direct method is not very satisfactory because of the large number and complication of the resulting mixture equations. However, most of the basic properties which would be involved are shown by simple kinetic theory to depend upon certain molecular properties. A more fundamental approach to the problem could be based on duplication of molecular properties. If a mixture could match on the macroscopic scale all of the molecular properties of another gas, it is reasonable that duplication of all the fluid properties and similarity parameters influencing flow and heat transfer processes would follow.

Expressions resulting from kinetic theory (Ref. 4) which relate the properties of a gas to those of its molecules are listed in the left-hand column of Table 1. Although these relationships are not necessarily the most accurate for an estimation of fluid properties, they do demonstrate which molecular properties are important. For a gas with a given pressure and temperature, these properties may be shown (by simple algebraic manipulation) to be dependent upon only three molecular characteristics: (1) molecular mass, (2) number of degrees of freedom, and (3) collision cross section, as summarized in the right-hand column. These three molecular characteristics then are those that should be duplicated; however, they may be related to specific gas properties.

Duplication of molecular mass may be achieved by requiring the molecular weights of the two gases to be equal,

$$MW]_{gas} = MW]_m \quad (1)$$

Similarly, as shown in Table 1, duplication of specific heat is equivalent to duplicating the number of degrees of freedom, or $f_{gas} = f_m$ when

$$c_p(T)]_{gas} = c_p(T)]_m \quad (2)$$

Since f is the only temperature dependent molecular characteristic involved in the analysis, it can be expected that the temperature variation of the gas properties listed in Table 1 would also be matched when the c_p temperature variation is duplicated. This is achieved when simulating air by hydrocarbon combustion gases because of the similarity between the variations of specific heat with temperature for these two gas mixtures (see Refs. 1 and 2 for a detailed discussion). This requirement must be considered and satisfied on an individual basis when applying this technique to other simulation cases. Although this, in general, is a rather difficult requirement to satisfy, it may be possible in many cases because of the characteristic variation of specific heat with temperature for most gases.

Obtaining an equivalent for collision cross section is not as straightforward. Cross-sectional areas can be easily defined for the spherical molecular model assumed by simple kinetic theory. However, these simple geometric cross sections do not exist for actual molecules. The effective volume occupied by the molecules, however, is given by the correction constant b which occurs in van der Waals equation of state. It seems reasonable that an effective molecular cross section should be related to the volume occupied by the molecule, that is, the constant b . A rather complete table of effective molecular collision radii for various gases which were obtained from experimental viscosity data is contained in Ref. 5. These collision radii squared are compared to their corresponding van der Waals constants (obtained from Ref. 6) in Fig. 1. A reasonably good correlation is observed for nonpolar molecules and atoms and for polar water vapor. Thus, van der Waals constant b is a simple index describing the collision cross section of the molecule and $\sigma_{gas} = \sigma_m$ if

$$b_{gas} = b_m \quad (3)$$

Equations (1), (2), and (3) then give the requirements which must be satisfied if a mixture is to simulate macroscopic properties of another gas or mixture at the same pressure and temperature. These equations may be rewritten by expanding the right side in terms of a multicomponent mixture. Fortunately, each of these properties may be accurately represented by a simple linear mixture equation:

$$MW]_{gas} = \sum_n x_n (MW)_n \quad (4)$$

$$c_p]_{gas} = \sum_n x_n c_{p_n} \quad (5)$$

$$b]_{gas} = \sum_n x_n b_n \quad (6)$$

In addition, it is necessary that the mixture satisfy continuity, which is expressed by the additional equation:

$$1] = \sum^n x_n \quad (7)$$

Equations (4) through (7) must be satisfied simultaneously with the additional boundary condition that $x_1, x_2, \dots, x_n \geq 0$. This set of simultaneous equations may be readily solved if the proposed mixture is limited to four components.

Reference 1 contains a group of solutions of Eqs. (4) through (7) for the case of simulating air at temperatures up to 4000°R with a mixture whose major component is the combustion gas formed from JP-4 and air. Although the combustion gas is a mixture in itself, it may be treated as a single component since its mixture properties are well known (Refs. 7 and 8). The differences in gas properties between diatomic air and hydrocarbon combustion gases are caused by the more complex CO₂ and H₂O molecules formed during combustion. If a combustion gas is to simulate air, it would be necessary to add simple monatomic gases to the combustion gases so that on the macroscopic scale the mixture would have the same average number of degrees of freedom as air. The composition and proportions of one air-equivalent mixture primarily composed of combustion gases are presented in Fig. 2. The mixture proportions are given for the various temperatures and the combustion gas fuel-air ratios used to specify the gas properties required in Eqs. (4) through (6). Equilibrium and transport properties of one of the air-equivalent mixtures of Fig. 2 are compared to the properties of air and the combustion gas alone ($\eta_c = 100$ percent) in Fig. 3. Although the properties of the combustion gas differ significantly from those of air over the entire temperature interval, the properties of the proposed mixtures agree quite well with the air properties. This behavior is remarkable because the solution of the equations only guarantees duplication of c_p at one temperature. Furthermore, as postulated by the theory, although viscosity or conductivity were not directly involved in the equations, they are nevertheless nearly matched over a large temperature interval. Thus, although the mixture proportions given in Fig. 2 depend upon a specified temperature, as each of these mixtures is heated or cooled, its thermal and transport properties will be found to vary with temperature in a similar manner (like those of air). Consequently, all of these mixtures are approximately equivalent. Most of the mixtures of Fig. 2 would have to have preheated or precooled additives to achieve the temperatures shown. Equilibrium temperatures of these air-equivalent mixtures are discussed in a later section.

3.0 EXPERIMENTAL VERIFICATION OF THEORY

Measurement of heat transfer and friction coefficients for a constant diameter tube provides a simple means of experimentally verifying this gas simulation theory.

Humble, Lowdermilk, and Desmon (Ref. 9) and Ramsey, Henderson, and Smith (Ref. 10) have measured heat transfer and friction coefficients for single tubes with air heated at temperatures up to 1500°R. The authors of Ref. 9 found that for a wide range of test conditions the tube heat transfer coefficient could be expressed by:

$$\frac{hD}{K_b} = 0.034 \left(\frac{GD}{\mu_b} \right)^{0.8} \left(\frac{c_{pb} \mu_b}{K_b} \right)^{0.4} \left(\frac{L}{D} \right)^{-0.1} \quad (8)$$

Because combustion gases have different properties than air (see Fig. 3), heat transfer coefficients for combustion gases should be about 12 percent lower than those for air as shown in Fig. 4.

This difference may be exploited to experimentally indicate the validity of replacing air with another mixture. Air at some initial temperature could be passed through a tube and the overall heat transfer coefficients measured for various flow rates. Then to experimentally establish the difference shown in Fig. 4, combustion gases alone could be passed through the tube at the same conditions. Finally, the heat transfer coefficients for an air-equivalent mixture could be measured in the same manner to attempt to show agreement with coefficients obtained with air rather than those of the combustion gases and demonstrate complete simulation for heat transfer testing. A similar comparison could be made with the tube friction coefficients to determine how accurately viscous aerodynamic phenomena may be reproduced by the air-equivalent mixture. *

Such tests have been made using air, combustion gases, and the mixtures defined by Fig. 2 as test media. The theoretically defined air-equivalent mixture employed by these tests was:

<u>Components</u>	<u>By Weight</u>	<u>By Volume</u>
Combustion Gas (f/a = 0.016)	0.8436	0.8441
Argon	0.0628	0.0454
Helium	0.0041	0.0296
Oxygen	0.0895	0.0809

*This is not a completely independent check of the theory because of the strong coupling between viscous boundary-layer and convective heat transfer phenomena.

The argon, helium, and oxygen which must be added to the combustion products are hereafter referred to as the additives.

3.1 APPARATUS

A schematic layout drawing of the equipment used for the experimental investigation is given in Fig. 5, and photographs of the assembled test apparatus are shown in Figs. 6 and 7. Air was obtained from a mobile gas turbine compressor unit at a pressure and temperature of about 55 psia and 750°R, respectively. It was ducted through a large surge tank, flow regulating valve, and orifice plate to a combustion chamber.

3.1.1 Combustor

A vortex-type combustor operating with JP-4 fuel was used to produce combustion gases. The fuel was supplied through a rotometer and flow-control needle valve. The combustor airflow was measured by an orifice plate and used in conjunction with the fuel flow rate to measure and set the operating fuel-air ratio. Because the simulation theory assumed a 100-percent combustion efficiency in specifying combustion-gas-based air-equivalent mixtures, some initial tests were made to determine and improve the combustor efficiency. By altering the fuel spray nozzle and flame holder design, the measured combustion temperature rises shown in Fig. 8 were obtained. Defining efficiency as the ratio of the measured to ideal temperature rise, combustion efficiencies from 90 to 95 percent were obtained during these tests. Assuming that incomplete combustion results in the formation of CO when the combustion efficiency is 90 percent or greater, the properties of the resulting combustion products (that is, a mixture of CO₂, CO, N₂, and O₂) differ only slightly from those shown in Fig. 3 for $\eta_c = 100$ percent. For tests with air only, the combustor served as a portion of the system ducting.

Since only a small portion of the mass flow required for operation of the combustor was needed for the tube test section, a tee was installed aft of the combustor which discharged most of the gas to the atmosphere through a choked nozzle (see Fig. 5). The mass flow through the test section was regulated by the exit gas control valve.

3.1.2 Heater

Chemical heating was usually sufficient for the combustion gas and mixture tests. A water-jacketed Kanthal electric heater located

just upstream of the test section was used as the heating source for the air tests and to adjust the combustion gas or gas mixture temperature.

3.1.3 Test Section

The test section consisted of a 0.5-in. O. D., 24-in. long, commercial, Inconel tube with a bellmouth entrance and a conical diffuser exit. A water jacket was placed around the tube in order to obtain nearly constant wall temperatures and effect a large temperature drop of the gas passing through the tube. Thin-walled, multipass, concentric, mixing chambers, as shown in Fig. 5, were installed at the test section entrance and exit. Baffles and screens were provided in the central passage of the mixing chambers to promote mixing of the test medium before it reached the pressure and temperature measuring stations. From the downstream mixing chamber the gas flowed through an orifice and flow control valve and was then discharged to the atmosphere. Three different orifice plates were used to accurately measure the tube mass flow.

3.1.4 Additive System

The additive gases were obtained premixed in commercial gas cylinders at a pressure of 1600 psia. They were introduced into the combustion products just upstream of the electric heater (see Fig. 5) at a pressure level of about 50 to 60 psia by a multi-orifice tube which extended across the combustion gas passage. The additive flow rate was measured by a gas flow rotometer. A chemical analysis indicated the following composition for the premixed additives:

	<u>By Volume</u>	
	<u>Experimental</u>	<u>Specified by Theory</u>
Argon	0.293	0.2918
Helium	0.188	0.1888
Oxygen	0.519	0.5194

3.2 INSTRUMENTATION

Locations of pressure, temperature, and mass flow instrumentation are also shown in Fig. 5. Because of the mixing chamber design quite uniform pressure and temperature distributions existed across the passage. Also, wall static pressure taps were located at the entrance to and exit from the test section. The test section wall temperatures were measured with waterproofed thermocouples embedded in the outer wall. These measuring stations were located at 2-in.

intervals and distributed randomly about the tube circumference. Pressures and temperatures were obtained at each orifice and rotometer location so that mass flow rates could be determined.

Pressures were measured with 5 and 15 psid transducers or Wallace-Tiernan gages, whereas temperatures were measured by means of chromel-alumel thermocouples and recorded on self-balancing potentiometers. All transducers and recorders were calibrated prior to each test.

3.3 PROCEDURE

For air runs the temperature in the entrance mixing chamber was set to the desired value. The water flow through the test section water jacket was set at a constant rate. When thermal equilibrium was established all pressure, temperature, and mass flow data were recorded. The gas mass flow through the test section was then incrementally varied over the range of a particular orifice plate while maintaining a constant inlet air temperature. About 15 to 20 minutes were allowed at each test point for the system to reach equilibrium.

For combustion gas test media the combustor fuel-air ratio was set and maintained at a constant value, usually $f/a \approx 0.016$. In this case, combustion provided the heating, and the electric heater was only used as a fine adjustment for the inlet temperature. All other operating procedures were identical with those outlined for the air runs. In several instances an air checkpoint was obtained at the beginning or end of a combustion gas test to clearly demonstrate the anticipated shifts of h and f .

For runs with the air-equivalent mixtures a combustion gas fuel-air ratio of 0.016 was set, and the mass flow passing through the tube was computed from observable data. The required additive flow was then admitted through a rotometer to the combustion products and the inlet temperature adjusted to the desired value by use of the heater. Once equilibrium was reached, the total and additive flow rates as well as combustor fuel-air ratio were recomputed and adjusted, if necessary, before test data were recorded. All other operating procedures were as previously described. A combustion-gas-alone data point was obtained at the beginning and end of each air-equivalent mixture test in order to assure that any measured shifts were caused by the additives rather than some random extraneous factor.

3.4 METHOD OF CALCULATION

Overall heat transfer coefficients for the test section were computed by equating the heat transfer from the gas to the heat transfer to the tube. Assuming, as in Ref. 9, that the gas temperature decreases linearly through the tube, the expression for h is

$$h = \frac{m_g c_{pb} (T_{t2} - T_{t1})}{\pi DL (T_w - T_b)} \quad (9)$$

where

$$T_b = \frac{T_{t1} + T_{t2}}{2} \quad (10)$$

represents the average or bulk gas temperature in the tube. The use of stagnation temperatures to define the bulk gas temperature is considered justifiable because of the very low velocities in the mixing chambers. Gas properties involved in the computation are defined at this bulk temperature. The wall temperatures used in Eq. (9) were obtained by averaging the measured values over the tube length. The thermocouples which were embedded in the wall were assumed to measure the inside wall temperature inasmuch as the calculated temperature differentials across the wall were small and within the measuring precision.

Friction coefficients were also computed by the method given in Ref. 9. From conservation of momentum considerations, the friction drop is obtained as

$$\Delta p_{fr} = (p_1 - p_2) - G^2 R \left[\frac{T_2}{p_2} - \frac{T_1}{p_1} \right] \quad (11)$$

For one-dimensional compressible flow

$$T = \frac{\gamma}{(\gamma - 1)R} \left(\frac{p}{G} \right)^2 + \sqrt{\left[\frac{\gamma}{(\gamma - 1)R} \left(\frac{p}{G} \right)^2 \right]^2 + 2T_t \frac{\gamma}{(\gamma - 1)R} \left(\frac{p}{G} \right)^2} \quad (12)$$

which allows computation of the static temperatures at the inlet and exit of the test section. By use of Eqs. (11) and (12) the tube friction coefficient may then be computed from

$$\frac{f}{2} = \frac{\rho_b \Delta p_{fr}}{4 \frac{L}{D} G^2} \quad (13)$$

where

$$\rho_b = \frac{1}{R} \left(\frac{p_1 + p_2}{T_1 + T_2} \right)$$

The Reynolds number based on tube diameter was computed in the usual way with the gas viscosity based on T_b .

The gas equilibrium and transport properties of the various test media required for these computations are summarized in Fig. 3. Air properties were primarily obtained from Ref. 11 and combustion gas properties from Refs. 7 and 8. Properties of the air-equivalent mixture were computed from the mixture equations suggested in Ref. 12. Some details of these calculational procedures are given in Refs. 1 and 3.

3.5 PRECISION OF DATA

To validate the theory, it is necessary only to determine the heat transfer and friction coefficients produced by one gas relative to those produced by another. This reduces the instrumentation problem to primarily one of repeatability. The method described by Kline and McClintock (Ref. 13) and later amplified by Thrasher and Binder (Ref. 14) was employed to estimate the repeatability of the test results prior to testing.

The precision of the instrumentation was estimated as:

Temperature	$\pm 5^\circ\text{R}$ in 500 to 700°R range $\pm 10^\circ\text{R}$ in 700 to 1500°R range
Pressure	± 5 psfa
Mass flow reading	± 3 percent of full-scale

Because errors in measurements of such factors as tube dimensions would be common to all test media they need not be considered. Based on the above precisions of the individual measurements, the following precisions of the test results were determined as outlined in the Appendix:

Heat transfer coefficient	± 4.2 percent
Friction coefficient	± 7.3 percent
Reynolds number	± 3.1 percent

The observed repeatability or scatter of the actual test data was within the above estimates for heat transfer coefficients and Reynolds numbers. However, experimental friction coefficients usually deviated about ± 15 percent from the mean. This could have been a result of some difficulties encountered with the static pressure leaks within the apparatus for some tests.

4.0 DISCUSSION OF EXPERIMENTAL RESULTS

4.1 HEAT TRANSFER DATA

Overall convective heat transfer coefficients were obtained for the tube test section over about one decade of Reynolds number from 10^4 to 10^5 . The results for each of the test media, (1) air, (2) combustion gases, and (3) the proposed air-equivalent mixture produced by adding argon, helium, and oxygen to the combustion gas, are presented in Fig. 9 for an initial gas temperature of 1200°R . Most of the experimental data were measured at this initial temperature which resulted in an average or bulk gas temperature of about 1050°R . Some additional coefficients were also measured with an initial temperature of 1400°R .

About seventy-five heat transfer coefficients were obtained with air at 1200°R (Fig. 9a). The level of h defined by the present tests is somewhat lower than that predicted by the correlation equation proposed by Humble, Lowdermilk, and Desmon (Ref. 9) which is given herein by Eq. (8). Since only relative differences in h produced by the various test media are of importance in verifying the proposed gas simulation theory, this rather small shift in level from a previous experiment is of little significance. Correcting the Ref. 9 estimate to a bulk temperature of 1050°R would slightly increase the difference between the present experiment and that of Ref. 9. The solid line shown in Fig. 9a is faired to best represent all of the air test data at a bulk temperature of 1050°R , and the scatter of the heat transfer coefficients about this line indicates a repeatability or precision of about 3.8 percent (maximum deviation from the mean).

Heat transfer coefficients measured with a combustion gas test medium at 1200°R are presented in Fig. 9b. The combustion gas fuel-air ratio varied between 0.0155 and 0.0172 except for one run (illustrated by the flagged symbols) where it was 0.022. Somewhat higher heat transfer coefficients were measured at this higher fuel-air ratio because of the different gas properties for this combustion gas mixture. These coefficients may be incrementally corrected to a fuel-air ratio of 0.016 by use of Eq. (8), in which case they are essentially in agreement with the remainder of the combustion gas data. Consistent with the air results, coefficients obtained with a combustion gas test medium were also somewhat lower than the predictions indicated by Eq. (8). The dashed line in Fig. 9b represents the mean of nearly sixty measured coefficients at a bulk temperature of 1050°R , and the deviation about the mean is approximately 5.2 percent. The somewhat increased scatter is primarily caused by the unsteady flow characteristics of the combustor. Heat transfer coefficients for heated air were also obtained

at the beginning of some of the combustion gas test medium experiments, shown by the solid symbols in Fig. 9b. These reference or check values for h demonstrate rather conclusively that the differences between the heat transfer coefficients produced by air and combustion gases are attributable to their different thermal and transport properties.

Because of the additional complexity of adding the prescribed additives to the combustion gases, fewer data were obtained with the air-equivalent mixture as the test medium. The proportions of the actual air-equivalent mixtures tested are tabulated in Table 2. They differed only slightly from the mixture specified by the theory. A typical comparison is made below:

<u>Experimental Tests</u>		<u>Specified by Theory</u>	
<u>Combustion Gas</u> <u>($f/a = 0.0165$)</u>	<u>By Weight</u> <u>0.8410</u>	<u>Combustion Gas</u> <u>($f/a = 0.0160$)</u>	<u>By Weight</u> <u>0.8436</u>
Argon	0.0639	Argon	0.0628
Helium	0.0041	Helium	0.0041
Oxygen	0.0910	Oxygen	0.0895

Thermal and transport properties of the air-equivalent mixtures tested were not essentially different from those calculated for the theoretically defined mixture and are only slightly different from the properties of air (see Fig. 3).

Room temperature additives were injected into the combustion gas at several points across the stream in order to promote mixing. On the average an additive molecule would undergo about 10^9 collisions before reaching the test section. Pressure and temperature profiles across the inlet mixing chamber were found to be uniform, indicating that good mixing was achieved.

Heat transfer coefficients resulting with an air-equivalent mixture test medium also at a temperature of 1200°R are summarized in Fig. 9c. During the air-equivalent tests, combustion-gas-alone check points were obtained (shown by solid squares in the figure) in order to be certain that the additives did influence the heat transfer coefficient.

4.2 FRICTION DATA

Friction coefficients obtained simultaneously with some of the heat transfer data of Fig. 9 are given in Fig. 10. Because of the difficulties encountered in the measurement of the static pressure at the exit

of the test section, the experimental scatter of these test results was greater than expected, and only selected results are shown. Friction coefficients for each of the test media, air, combustion gases, and the air-equivalent mixtures, are shown in Figs. 10a, b, and c, respectively.

4.3 COMPARISON BETWEEN TEST MEDIA

The effectiveness of the proposed gas simulation technique may be observed by comparison of the heat transfer coefficient results of Figs. 9a, b, and c. The percentage deviation of the measured heat transfer coefficients from the mean curve defined for air (that is the solid curve in Fig. 9a) is given as a function of Reynolds number in Fig. 11a. To avoid the confusion which would be introduced by a large number of symbolized points the air and combustion gas results of Figs. 9a and b are represented by their repeatability bands and mean faired curves in Fig. 11a.

As illustrated by Fig. 11a the precision of the data is such that the heat transfer coefficients measured with air and combustion gases do not overlap, and the differences produced by these two test media can be clearly demonstrated. Reference coefficients obtained for air during the combustion gas tests are observed to agree with the remainder of the air data as they should, indicating that the lower heat transfer coefficients for combustion gases are not attributable to an accidental factor.

The mean curve representing all combustion gas coefficients is about 11 percent lower than the mean air curve, whereas a 12-percent difference would be predicted by Eq. (8) (see Fig. 4). Although this minor discrepancy is well within the experimental repeatability, it may be caused by radiation from the CO_2 and H_2O molecules in the combustion gases. Effects of radiation are discussed in Section 5.3.

Figure 11a also clearly demonstrates that the heat transfer coefficients produced by the air-equivalent mixtures agreed with the coefficients obtained for air, within repeatability or precision of the air results, whereas the combustion gas reference coefficients taken during some of the same experimental tests are in the range established for combustion gases. Thus, it seems assured that the shift in the level of h effected by the addition of argon, helium, and oxygen to the combustion products is attributable to modifying the bulk or macroscopic gas properties of the combustion gas mixture, rather than to some factor not germane to the experiment.

Some additional heat transfer coefficients were measured with an initial gas temperature of 1400°R which provided a bulk temperature of about 1200°R (Fig. 11b). Complete test results at this temperature were not obtained because of a failure of an electrical heating element. However, from those data available it is apparent that the air-equivalent mixtures at the higher temperature also produced heat transfer coefficients which agreed very well with those of air.

One additional heat transfer experiment was made to determine how sensitive the attendant shift of h is to the amount of additives put into the combustion products. The solid diamond symbol in Fig. 11a represents the heat transfer coefficient obtained with an additive flow of 21 percent of the total, or about one-third more than specified by the theory. The shift of h from the combustion gas level which was produced by this amount of additives was also about one-third too large.

Examination and comparison of the friction coefficients (Fig. 10) indicates similar conclusions regarding the effectiveness of this gas simulation scheme. Since the friction coefficient for the tube is closely related to its heat transfer coefficient, through the Reynolds analogy for example, the reproduction of air friction coefficients by the air-equivalent mixture is not a completely independent proof of the theory.

From Reynolds analogy,

$$f/2 = \frac{h}{\rho_b v c_{p_b}} \quad \text{or at constant } Re_D, \quad f/2 \propto \frac{h}{c_{p_b} \mu_b}$$

The difference in the friction coefficients between air and combustion gases indicated in Fig. 10 corresponded (through the above relationship) at a constant Re_D to the difference in heat transfer coefficient shown in Fig. 9. In addition, friction coefficients for the air-equivalent mixtures tended to agree with those obtained for air.

Thus, the measured heat transfer and friction coefficients consistently demonstrate that air may be simulated for steady-state aerodynamic and heat transfer tests by the addition of small amounts of argon, helium, and oxygen to a hydrocarbon combustion gas. Or, more generally, as suggested by the theoretical analyses, it is possible to specify a gas mixture which will behave like another gas for gas dynamic and heat transfer test purposes. Furthermore, the simulation of air did not occur just at a single temperature, but, since the test media were cooled several hundred degrees in passing through the tube, simulation of a temperature dependent process was achieved. This fact is important in extending this technique to the simulation of high temperature compressible flows where molecular vibration is active. Such flows are strongly dependent on the variation of the specific heat ratio between the stagnation and static temperatures.

5.0 LIMITATIONS OF AIR-EQUIVALENT MIXTURES

5.1 EQUILIBRIUM TEMPERATURE

By applying conservation of energy the equilibrium temperatures for various air-equivalent mixtures have also been computed for the case of room temperature additives and a combustion efficiency of 100 percent (see Ref. 1 for details). The temperatures which may be achieved with the mixture employed in the present tests for combustion gases having various fuel-air ratios are summarized in Fig. 12. The oxygen component of this air-equivalent mixture decreases as the combustion gas fuel-air ratio or temperature is increased (Fig. 2) until at $f/a > 0.0415$, the solution of Eqs. (4) through (7) fails to satisfy the boundary condition. This limits the maximum temperature which could be obtained with room temperature additives to about 2850°R (Fig. 12). Preheating the additives, of course, could increase the equilibrium temperatures somewhat. Additional solutions contained in Ref. 1 indicate that addition of nitrogen instead of oxygen (that is, argon, helium, and nitrogen additives) allows the use of combustion gases at higher fuel-air ratios and air could be simulated up to about 3300°R (see Fig. 12)*.

In the analysis an upper temperature limit of 4000°R was imposed in order to avoid the complication of molecular dissociation and the attendant nonequilibrium effects. Much higher mixture temperatures could probably be achieved since the energy stored in the chemical bonds of certain substances allows combustion temperatures to almost 10,000°R. Because of complications introduced by molecular dissociation at these higher temperatures, each application of this simulation technique must be considered on an individual basis. Some calculations of the degree of dissociation and energy invested in the dissociated species for air and hydrocarbon combustion products are contained in Ref. 15 and indicate that the nonequilibrium effects of dissociation on this simulation scheme may not be serious at temperatures below about 5000R°. Additional nonequilibrium effects on the simulation method caused by molecular vibration are discussed in some detail in Ref. 1.

*In wind tunnel applications these equilibrium temperatures could correspond to the tunnel stagnation temperature.

5.2 WATER VAPOR CONDENSATION

In the theoretical analysis it was assumed that the water formed during production of the combustion gases would remain in the vapor state. Also, the experimental tests were conducted in a manner to avoid water condensation. Condensation of any of the air-equivalent mixture components, however, would completely foil the simulation attempt. A condensation map for the mixture employed in the present tests at a temperature of 1800°R is given in Fig. 13a to demonstrate the regions in which condensation would restrict the application of this technique in gas dynamic testing. Although the phenomena and conditions for water condensation in wind tunnels are quite complicated, condensation would normally be expected to occur between the vapor saturation line and the 90-deg supersaturation line shown in the figure. Depending upon the pressure level, this mixture may be used to simulate airflows with local Mach numbers below about 4.0. A similar map is contained in Fig. 13b for the mixture of combustion gas, argon, helium, and nitrogen at a temperature of 3000°R which can simulate air at local Mach numbers to about 6.0. The problem of water vapor condensation and its consequences are discussed in more detail in Ref. 15.

5.3 RADIATIVE HEAT TRANSFER

While gases which have symmetrical molecules such as oxygen or nitrogen do not radiate at wave lengths of importance in radiant heat transmission, water vapor and carbon dioxide possess radiative characteristics which usually should be considered. Since these two gases comprise about 8 to 9 percent of the combustion gas or air-equivalent mixture by weight in the present tests, these two test mediums will also transfer a small amount of heat by radiation which would not be transferred with an air test medium. Radiative heat transfer coefficients have been determined from the experimental data for the air-equivalent mixtures by use of the method suggested by Hottel and Egbert (Ref. 16). As shown in Fig. 14 radiation heat transfer is a small portion of the convective heat transfer measured in the present tests. However, it could be significant with combustion gases containing a much larger proportion of CO₂ or H₂O. As a result, this factor might limit the usefulness of air-equivalent mixtures for heat transfer testing which employ combustion gases with high fuel-air ratios.

6.0 CONCLUDING REMARKS

Initially this investigation was undertaken to determine if a high temperature hydrocarbon combustion gas could be used as a wind tunnel test medium and produce the same test results that would have been obtained in air. The analysis and experimental tests illustrate that the addition of small amounts of certain gases to the combustion gas results in a new mixture which will behave like heated air for heat transfer and aerodynamic test purposes. This simulation technique may have much wider application inasmuch as it offers a method to avoid the use of some undesirable or impractical test medium by replacing it with a more convenient mixture of gases.

As an example, the set of simulation equations have also been used to attempt to define mixtures with the same macroscopic properties as the gas mixtures which are believed to compose the atmospheres of Mars and Venus. Mixtures considered contained air as the primary component, and the additives were specified to adjust the properties of air to those of the desired planetary atmosphere. Table 3 contains some examples of mixtures which should simulate these planetary atmospheres at low temperatures. None of these mixtures is particularly desirable, but they do demonstrate another application of this technique. It is not known if the need will arise in the future to simulate flight conditions entering and departing from these planets; however, this simulation technique offers a possibility of conducting such tests in existing test facilities.

The choice of a simulation mixture in place of the usual test medium will be strongly influenced by the economics of the particular situation. The use of modified combustion gases to replace high temperature air is certainly economically feasible. However, this may not be the case in the simulation of other planetary atmospheres. The mixtures shown in Table 3 were only given as examples, and a more complete study may specify mixtures which are more attractive from an economic standpoint.

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APPENDIX ESTIMATE OF REPEATABILITY OF MEASURED HEAT TRANSFER COEFFICIENTS

The repeatability has been estimated for heat transfer coefficients determined by:

$$h = \frac{m_g c_{p_b} (T_{t_2} - T_{t_1})}{S (T_w - T_b)}$$

Typical values of the physical measurements and their precisions are:

$$m_g = 0.0600 \pm 0.0018 \text{ lb}_m/\text{sec}$$

$$c_{p_b} = 0.258 \pm 0.001 \text{ Btu/lb}_m \cdot ^\circ\text{R}$$

$$(T_{t_2} - T_{t_1}) = 460^\circ \pm 10^\circ\text{R}$$

$$T_w = 585^\circ \pm 5^\circ\text{R}$$

$$T_b = 1270^\circ \pm 10^\circ\text{R}$$

and

$$h = 0.0495 \text{ Btu/ft}^2\text{-sec-}^\circ\text{R}$$

This calculation has been made for a tube 24 in. long and with a 0.402-in. inside diameter ($S = 0.2105 \text{ ft}^2$).

It is not necessary to determine the accuracy with which S may be measured since only differences in h are important. Similarly, c_{p_b} is obtained from tables by knowing T_b , and it is only necessary to specify how accurately values may be selected from the table and not how accurate the tables may be.

$$\frac{\partial h}{\partial m_g} = \frac{c_{p_b} (T_{t_2} - T_{t_1})}{S (T_w - T_b)} ; \Delta h(m_g) = \frac{\partial h}{\partial m_g} \delta m_g = 5.34$$

(where δm_g is the precision of m_g and $\Delta h(m_g)$ represents the repeatability of h due to precision of m_g).

$$\frac{\partial h}{\partial c_{p_b}} = \frac{m_g (T_{t_2} - T_{t_1})}{S (T_w - T_b)} ; \Delta h(c_{p_b}) = \frac{\partial h}{\partial c_{p_b}} \delta c_{p_b} = 0.57$$

$$\frac{\partial h}{\partial (T_{t_2} - T_{t_1})} = \frac{m_g c_{p_b}}{S (T_w - T_b)}$$

$$\Delta h (T_{t_2} - T_{t_1}) = \frac{\partial h}{\partial (T_{t_2} - T_{t_1})} \delta (T_{t_2} - T_{t_1}) = 4.52$$

$$\frac{\partial h}{\partial T_w} = - \frac{m_g c_{p_b} (T_{t_2} - T_{t_1})}{S (T_w - T_b)^2}; \Delta h (T_w) = \frac{\partial h}{\partial T_w} \delta T_w = -1.09$$

$$\frac{\partial h}{\partial T_b} = \frac{m_g c_{p_b} (T_{t_2} - T_{t_1})}{S (T_w - T_b)^2}; \Delta h (T_b) = \frac{\partial h}{\partial T_b} \delta T_b = 2.18$$

Then,

$$\Delta h = \pm \sqrt{\Delta h (m_g)^2 + \Delta h (c_{p_b})^2 + \Delta h (T_{t_2} - T_{t_1})^2 + \Delta h (T_b)^2 + \Delta h (T_w)^2}$$

$$\Delta h = \pm 0.00206 \text{ Btu/ft}^2\text{-sec-}^\circ\text{R}$$

Or, the repeatability of h is about ± 4.2 percent of the measurement. In a similar manner, the repeatabilities of the friction coefficients and tube Reynolds number were estimated as ± 7.3 percent and ± 3.1 percent, respectively. Although it is possible for all errors to act in the same direction and produce larger maximum errors, if sufficient data are obtained, the mean value should be within the above limits.

TABLE 1
SUMMARY OF KINETIC THEORY RELATIONSHIPS

	<u>Basic Equations</u>	<u>Molecular Characteristics Involved</u>
1.	$\bar{v} = \sqrt{8kT/\pi m}$	m
2.	$p = \frac{\pi}{8} N m \bar{v}^2$	--
3.	$c_v = \frac{f}{2} N_0 k$	f
4.	$c_p = \frac{f}{2} N_0 k + N_0 k$	f
5.	$\gamma = c_p/c_v$	f
6.	$\bar{E} = \frac{f}{2} kT$	f
7.	$Z = \sigma N \bar{v}$	σ, m
8.	$\lambda = 1/\sqrt{2} \sigma N$	σ
9.	$\mu = m \bar{v}/\sqrt{18} \sigma$	m, σ
10.	$K = \bar{v} f k/\sqrt{72} \sigma$	f, σ, m
11.	$D_S = \sqrt{2} \bar{v}/3 N \sigma$	σ, m

TABLE 2
PROPORTIONS OF EXPERIMENTAL AIR-EQUIVALENT MIXTURES BY WEIGHT

	Combustion Gas	Argon	Helium	Oxygen
Theory	0.8436	0.0628	0.0041	0.0895
Experiment $Re_D \times 10^{-4}$				
2.27	0.8430	0.0631	0.0041	0.0898
2.66	0.8417	0.0636	0.0041	0.0906
3.07	0.8428	0.0631	0.0041	0.0900
3.63	0.8370	0.0655	0.0042	0.0933
4.08	0.8348	0.0664	0.0043	0.0945
4.72	0.8490	0.0607	0.0040	0.0863
5.45	0.8450	0.0623	0.0040	0.0887
5.91	0.8396	0.0644	0.0042	0.0918
6.70	0.8317	0.0676	0.0043	0.0964
7.32	0.8422	0.0646	0.0040	0.0892
7.82	0.8436	0.0628	0.0041	0.0895
8.53	0.8444	0.0625	0.0040	0.0891
9.47	0.8447	0.0624	0.0040	0.0889
5.09*	0.7926	0.0833	0.0054	0.1187

*Additive flow rate one-third more than specified by theory.

TABLE 3
MIXTURES TO SIMULATE PLANETARY ATMOSPHERES AT A TEMPERATURE OF 600°R

MARS

Estimated Atmosphere	Simulation Mixtures - Percent by Weight			
Nitrogen - 96%	Air - 52.53	Air - 80.30	Air - 56.15	
Argon - 3%	Heptane - 9.34	Argon - 11.97	Argon - 21.10	
Carbon Dioxide - 1%	Argon - 35.27	Helium - 1.08	Helium - 3.20	
	Helium - 2.86	Acetonitrile* - 6.65	Thiophene - 19.55	

VENUS

Estimated Atmosphere	Simulation Mixture	
	Percent by Weight	Percent by Volume
Carbon Dioxide - 90%	Air - 55.72	85.33
Nitrogen - 10%	Xenon - 9.93	3.36
	Ethforane** - 32.89	10.57
	Freon 14 - 1.46	0.74

* Toxic in large amounts
 ** Freon family - nontoxic

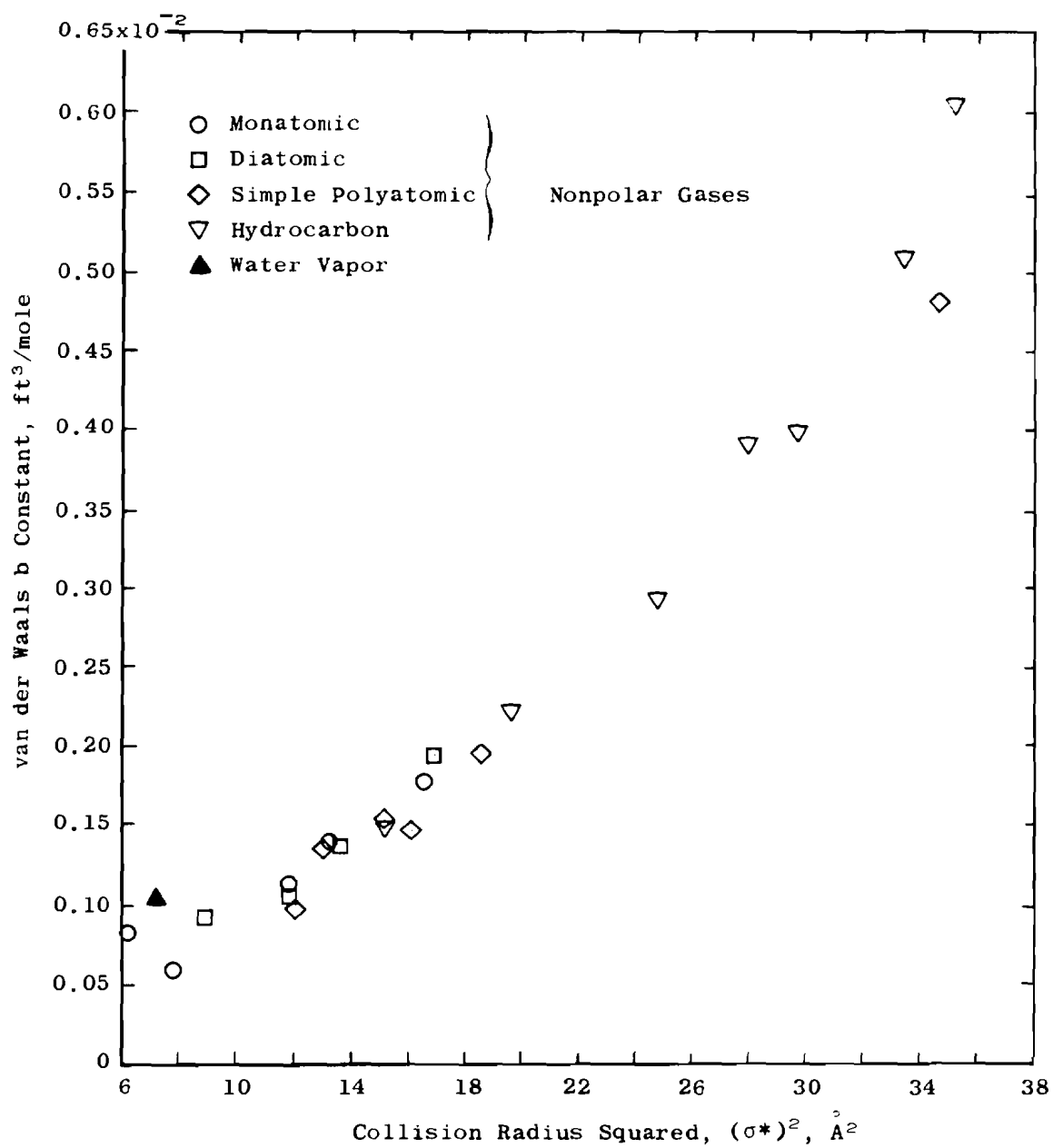


Fig. 1 Correlation of van der Waals b Constant and Collision Cross Section for Nonpolar Gases and Water Vapor

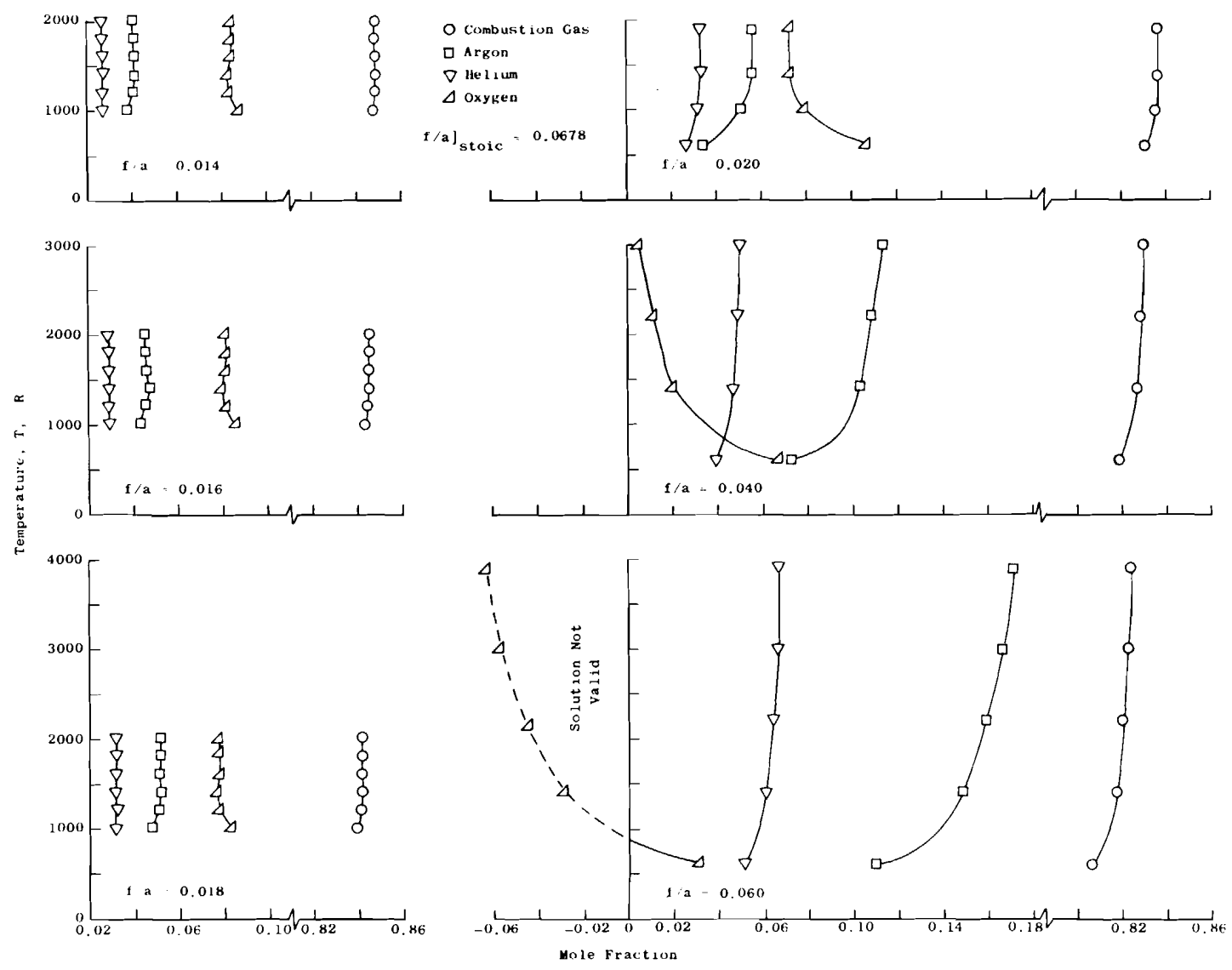


Fig. 2 Composition and Proportions of an Air-Equivalent Mixture with a Combustion Gas Base (Ref. 1)

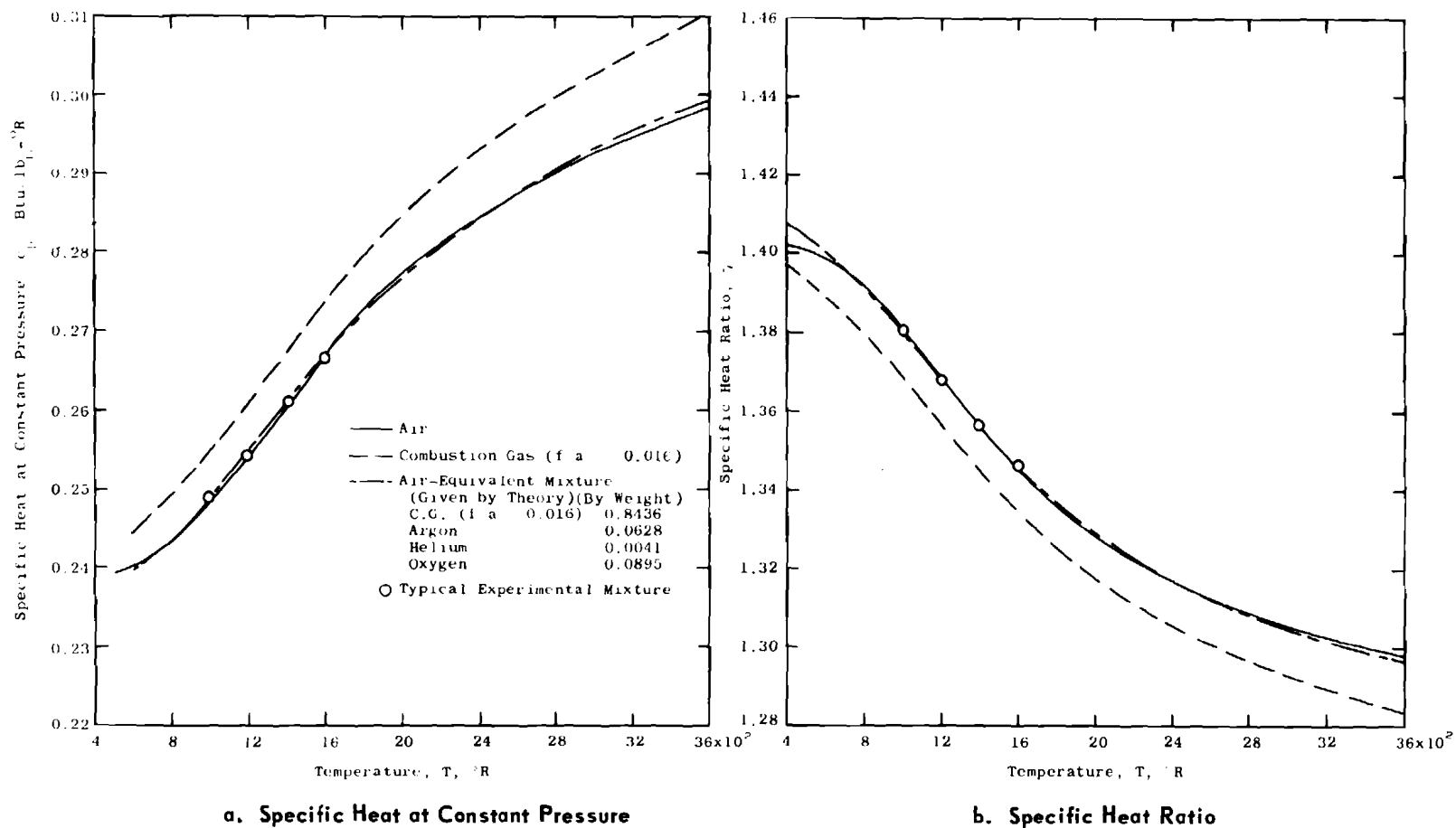
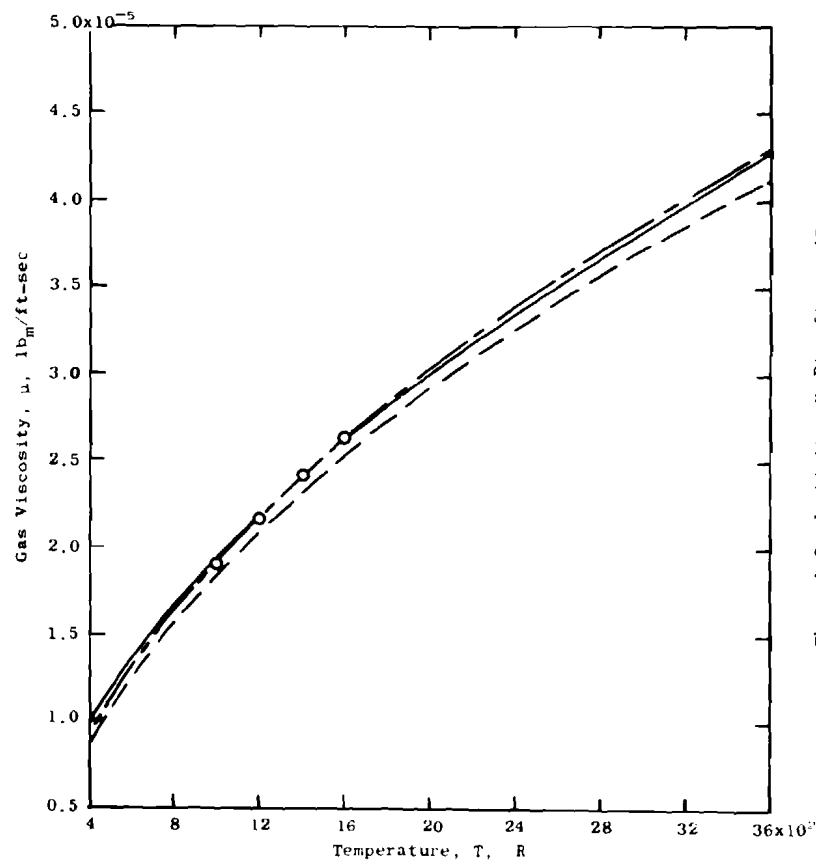
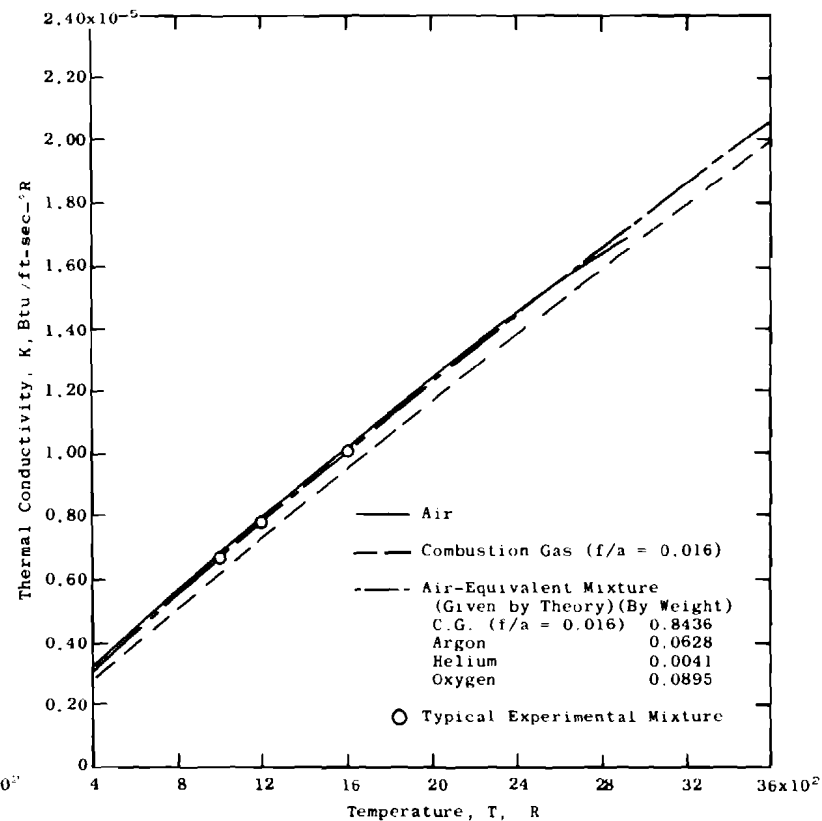


Fig. 3 Thermal and Transport Properties of Various Test Media



c. Viscosity



d. Thermal Conductivity

Fig. 3 Concluded

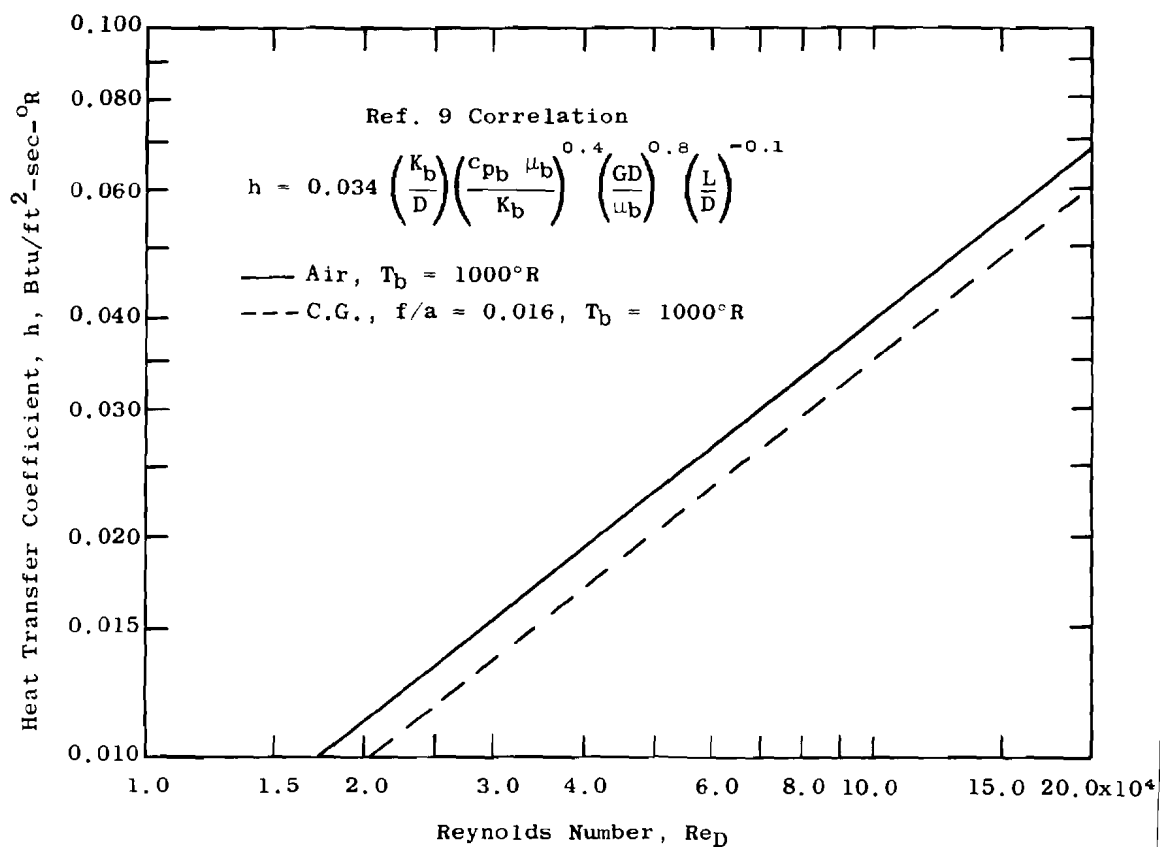


Fig. 4 Overall Convective Heat Transfer Coefficient for Tubes with Air and Combustion Gas Test Media

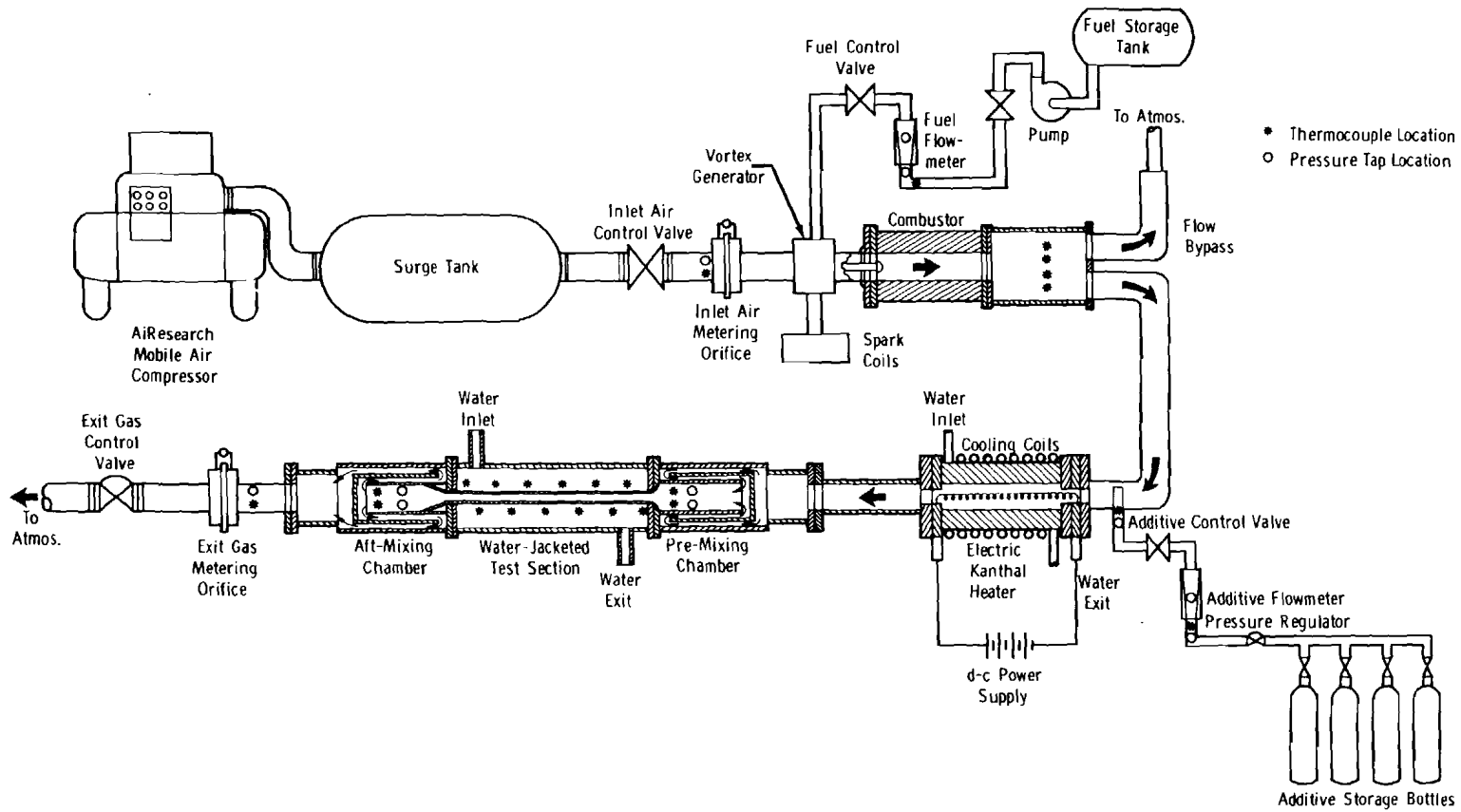


Fig. 5 Schematic of Experimental Test Apparatus

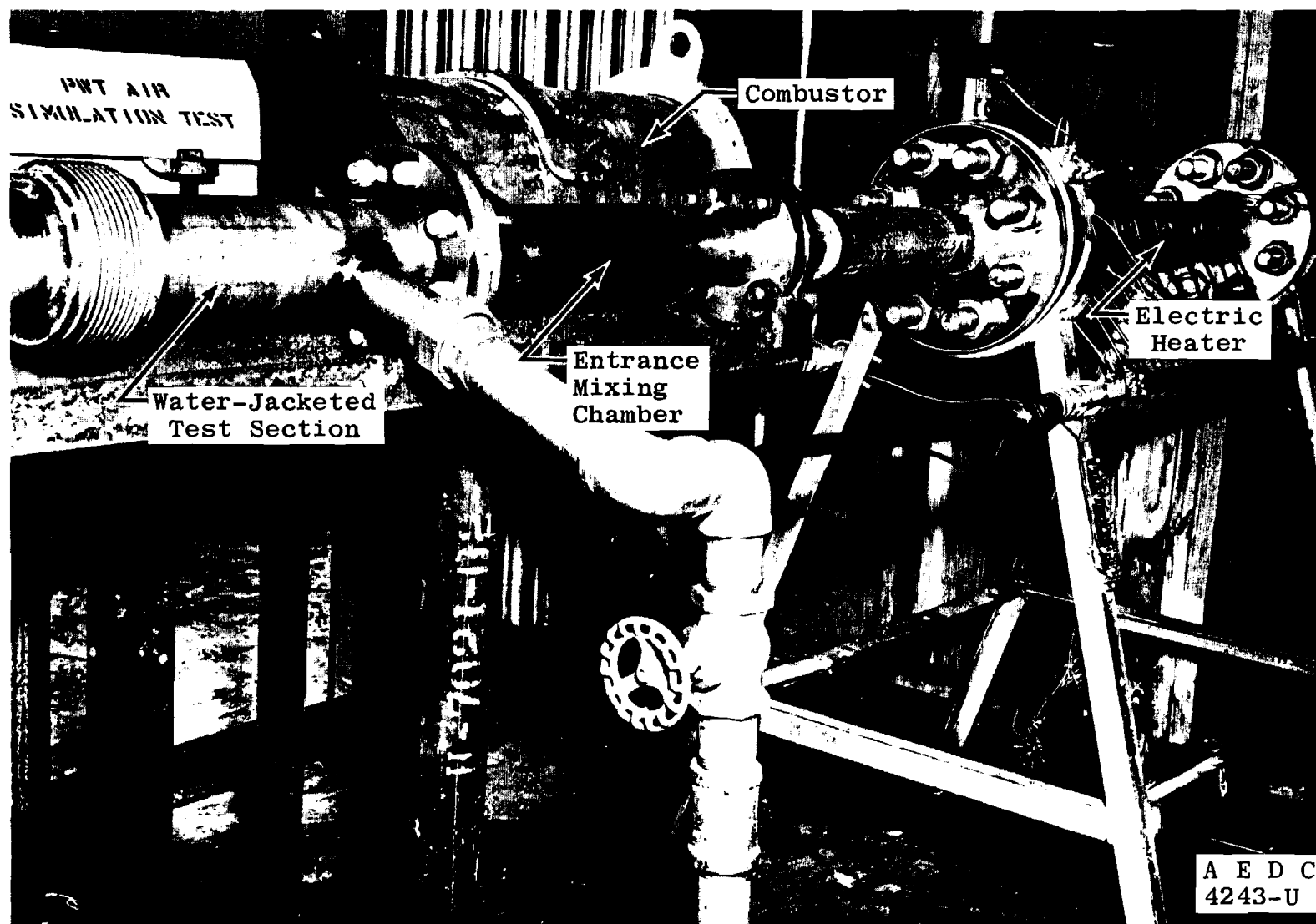


Fig. 6 Photograph of Test Apparatus

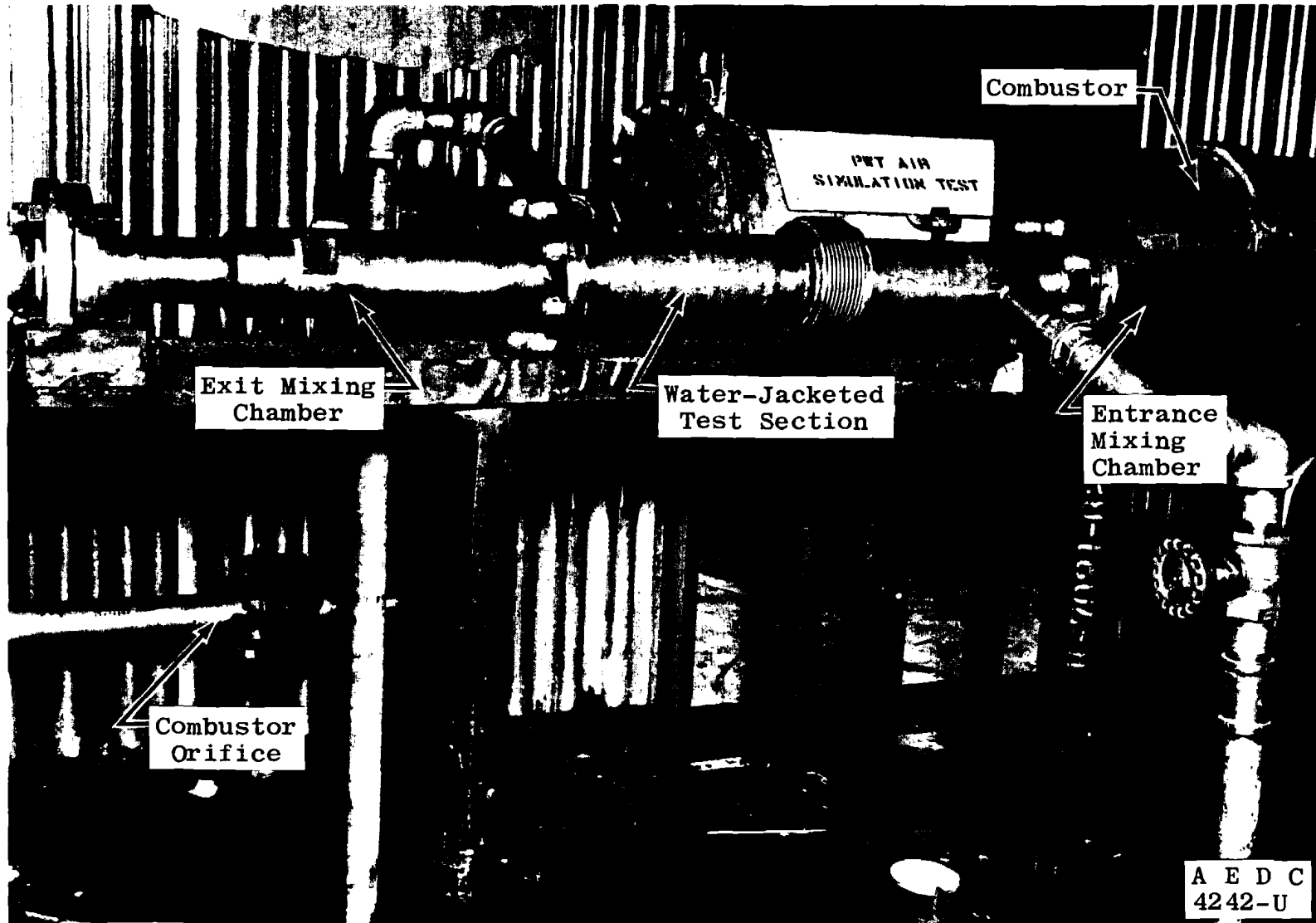


Fig. 7 Photograph of Water-Jacketed Test Section

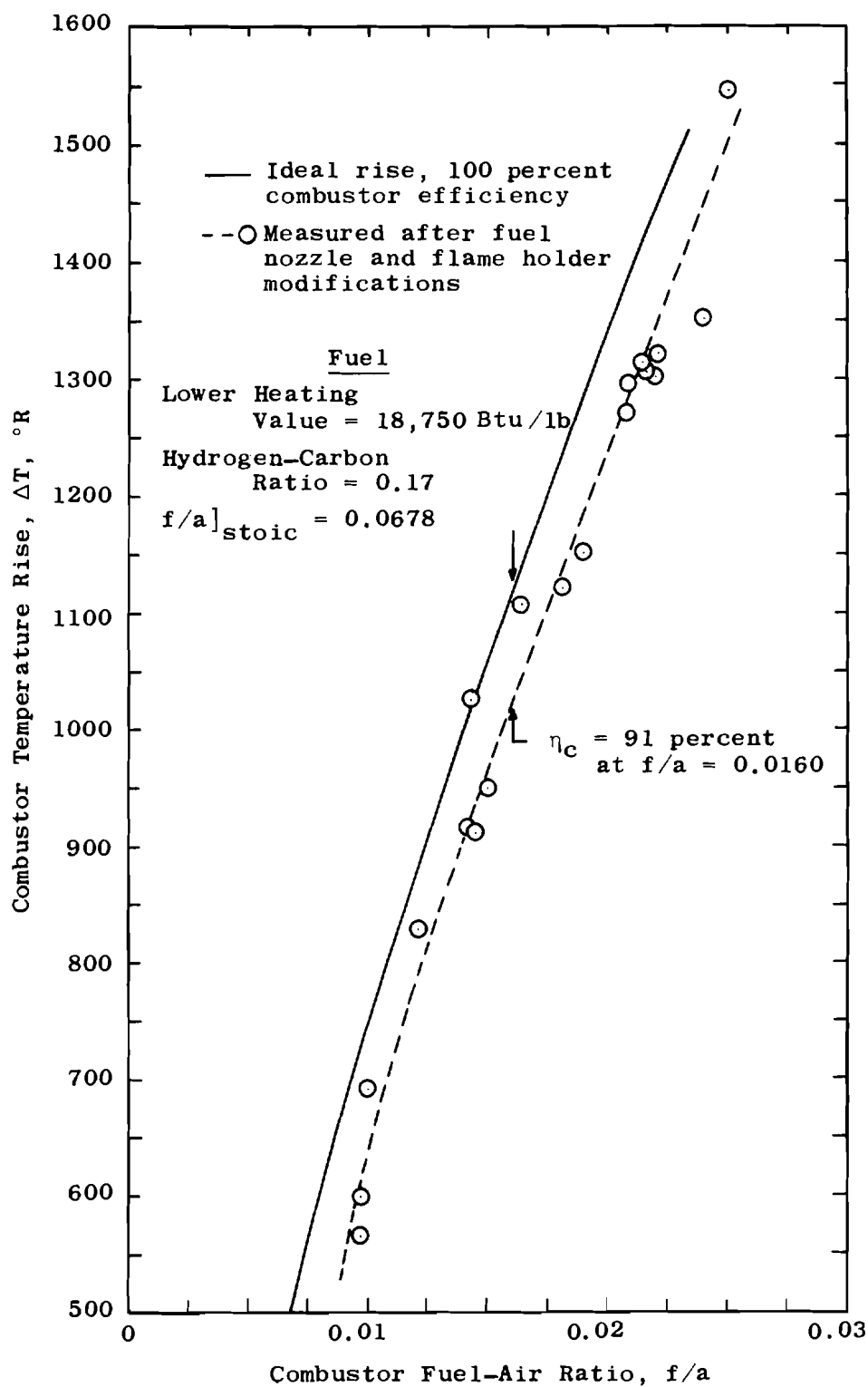
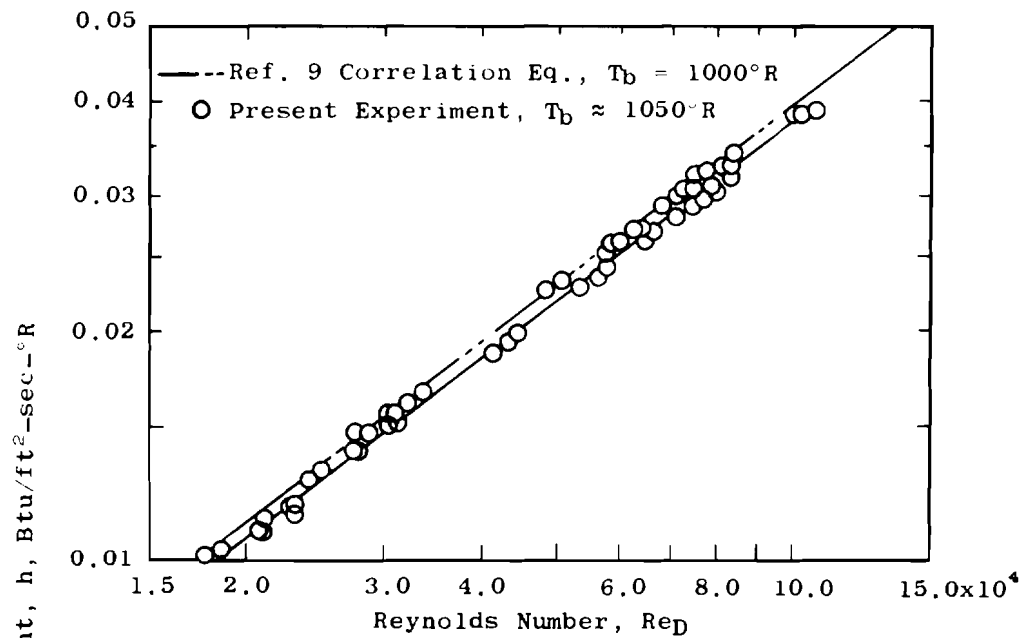
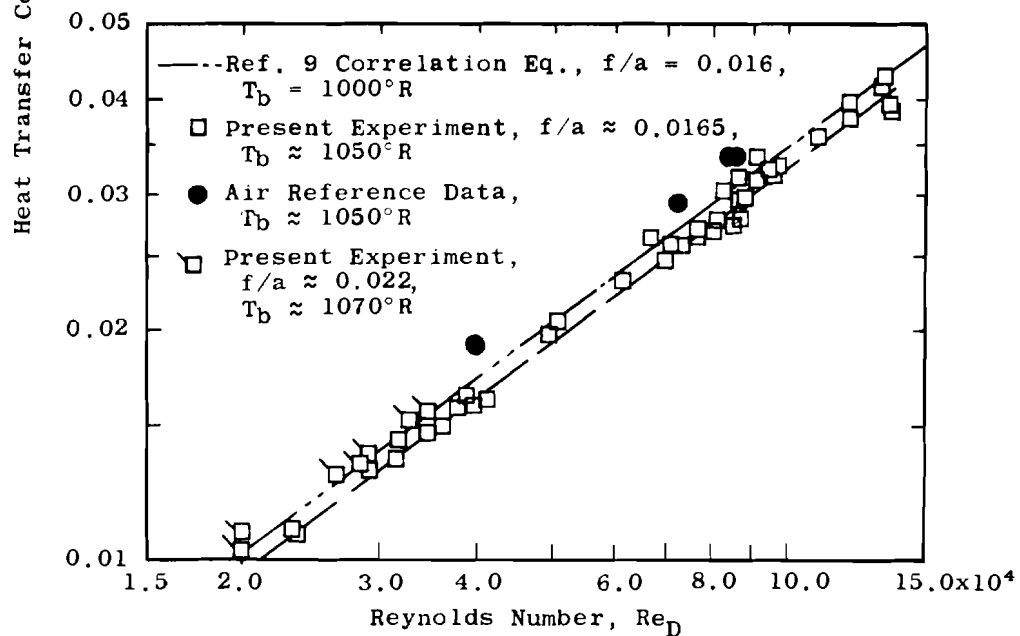


Fig. 8 Combustor Temperature Rise at Various Operating Fuel-Air Ratios

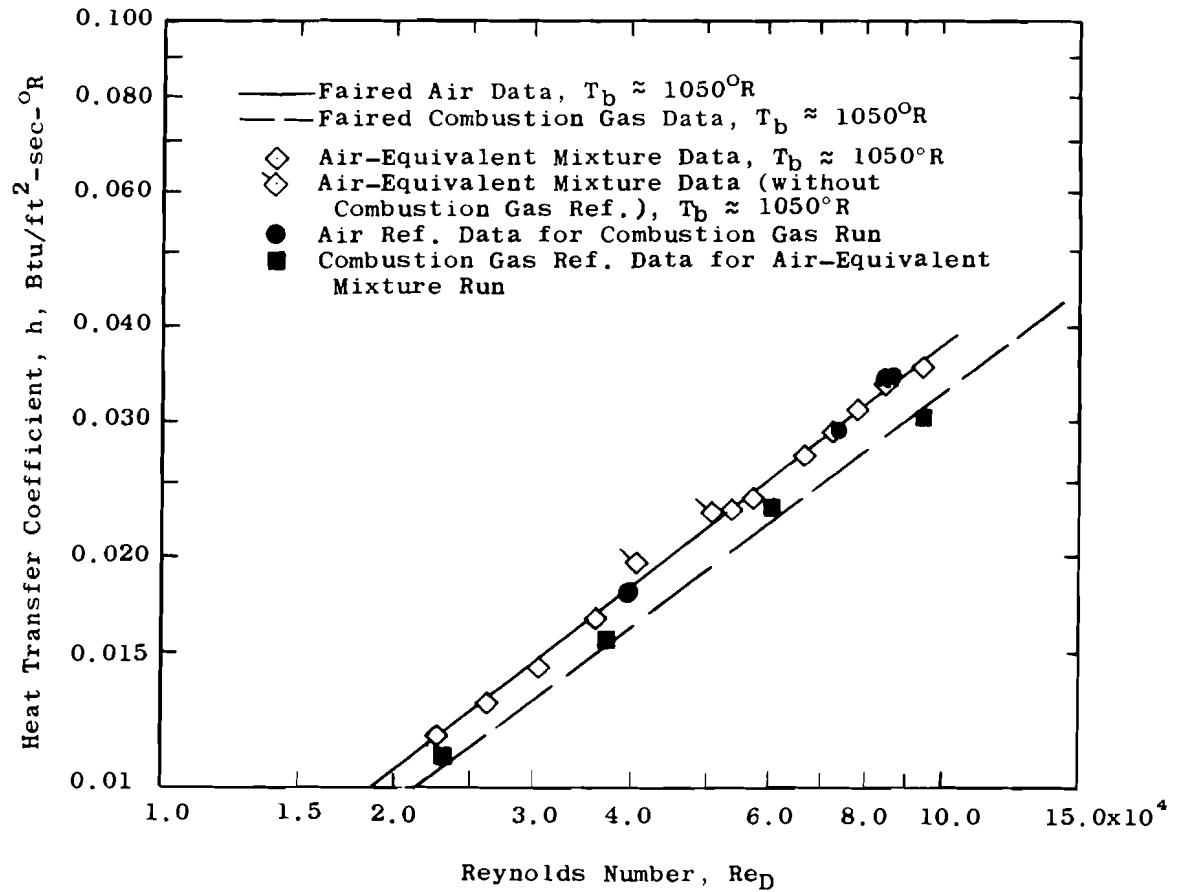


a. Air



b. Combustion Gas

Fig. 9 Convective Heat Transfer Coefficient Data for Each Test Medium



c. Air-Equivalent Mixture

Fig. 9 Concluded

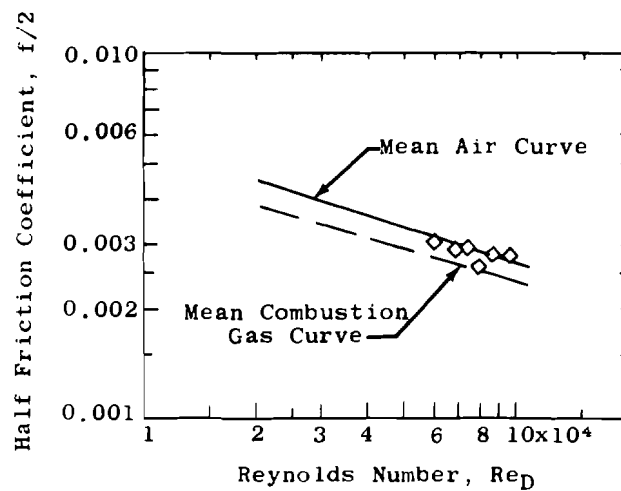
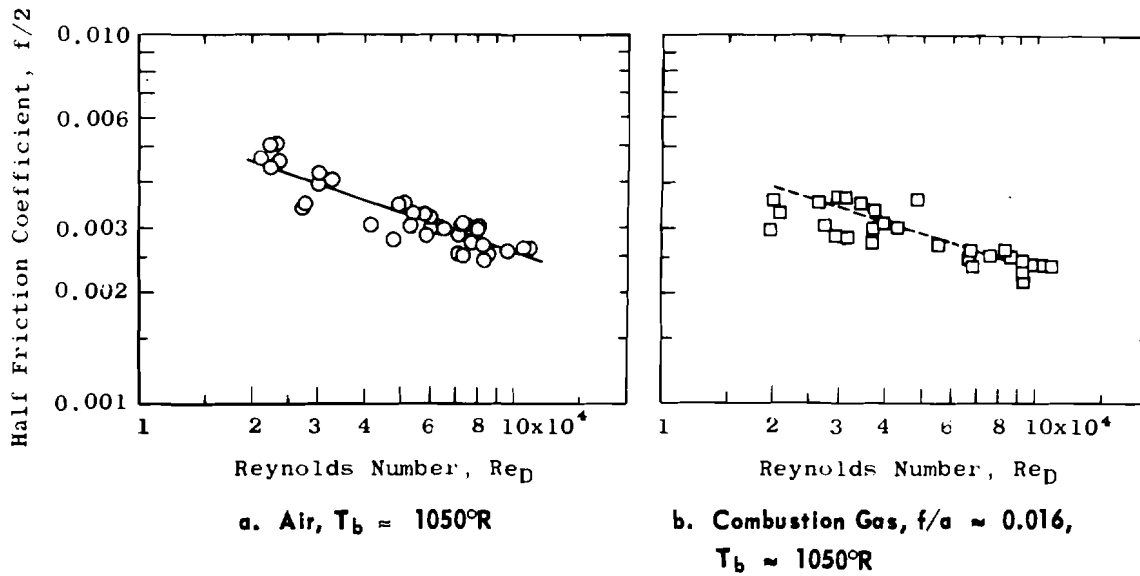


Fig. 10 Friction Coefficient Data for Each Test Medium

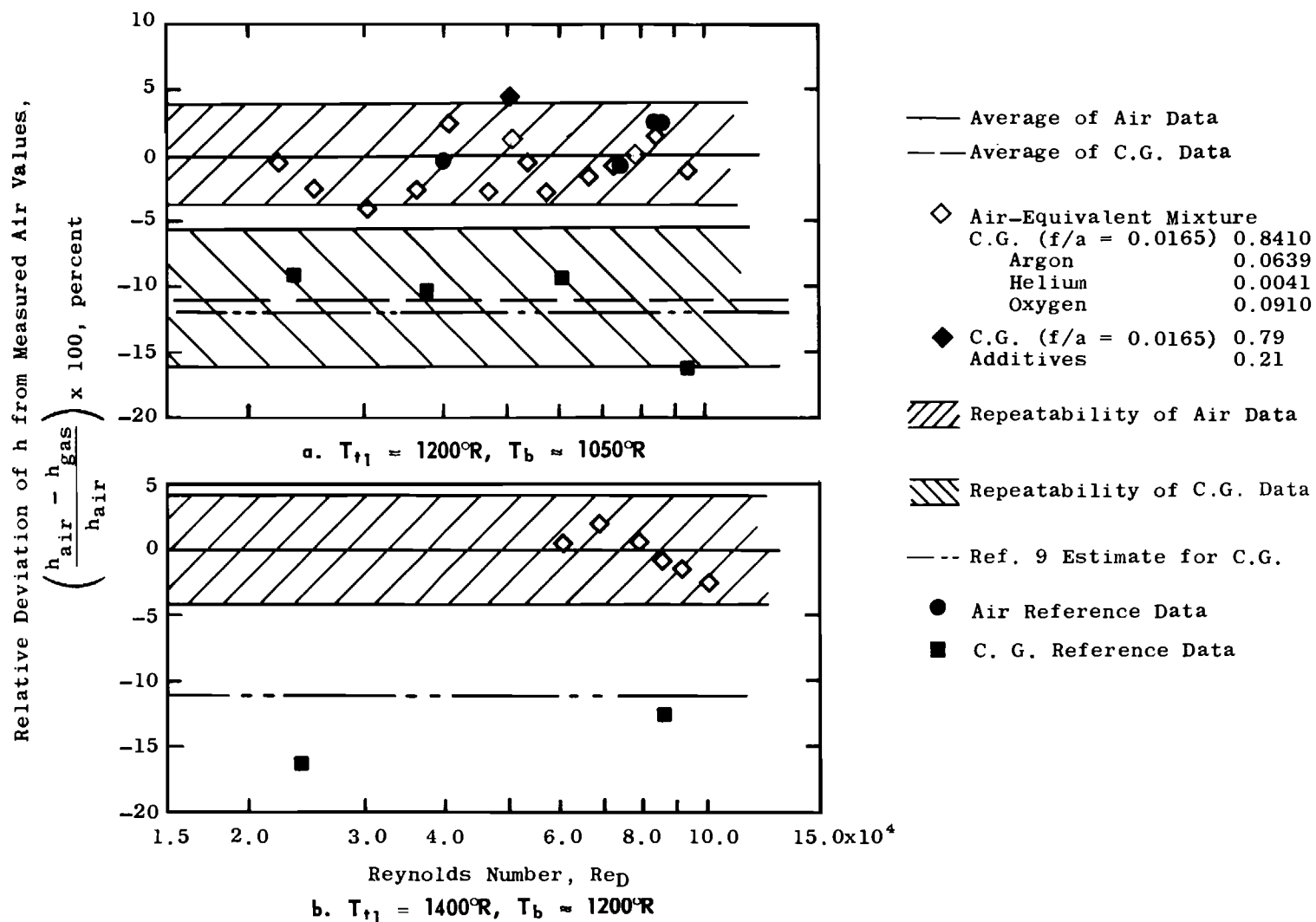


Fig. 11 Comparison of Heat Transfer Results for Various Test Media

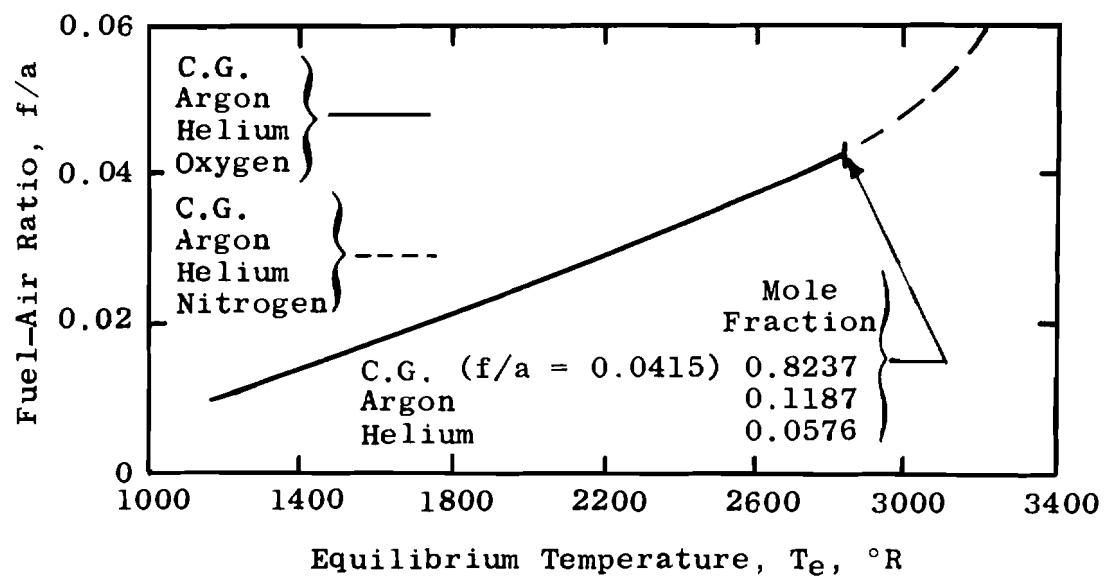
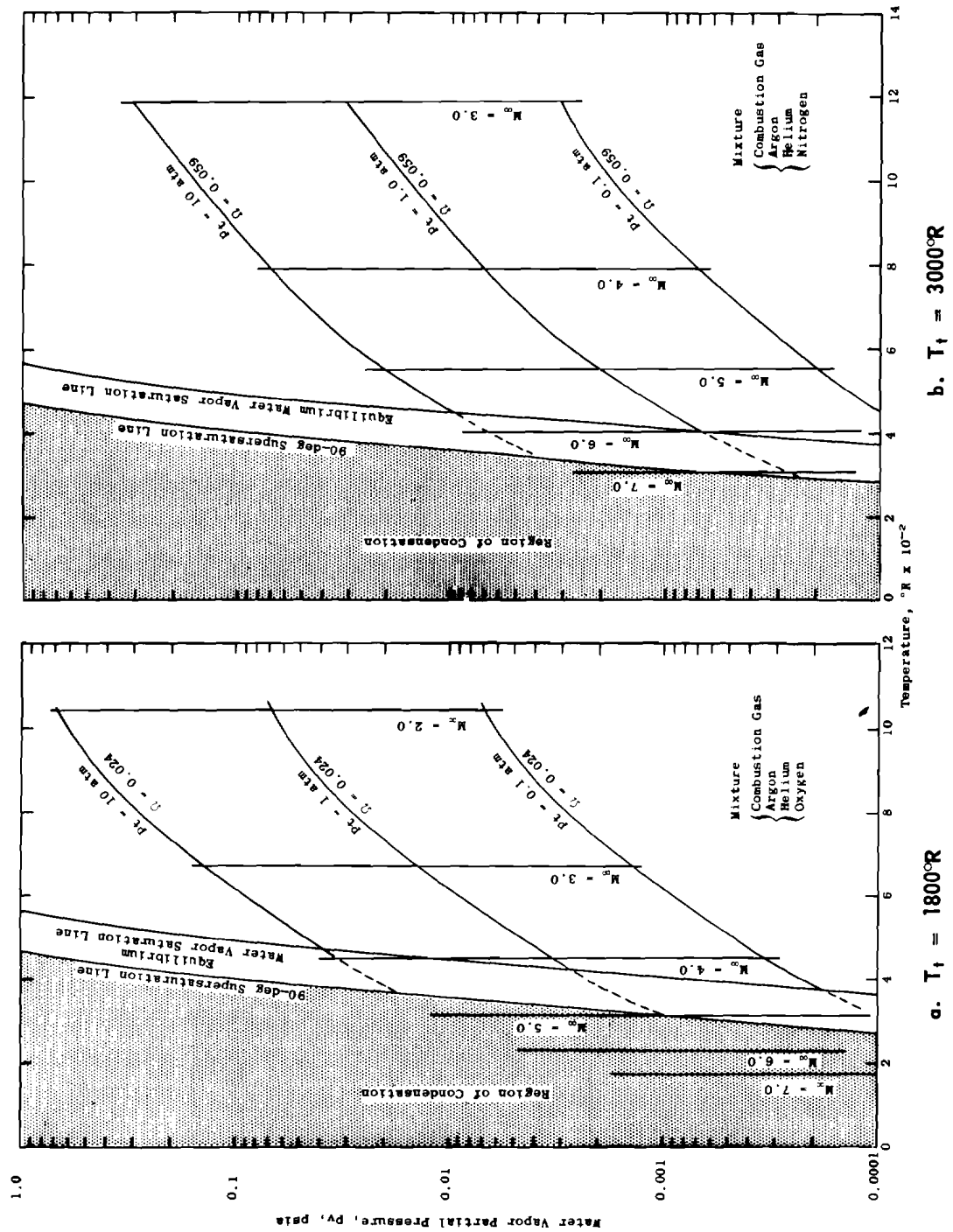


Fig. 12 Mixture Equilibrium Temperatures with Additives at 70°F



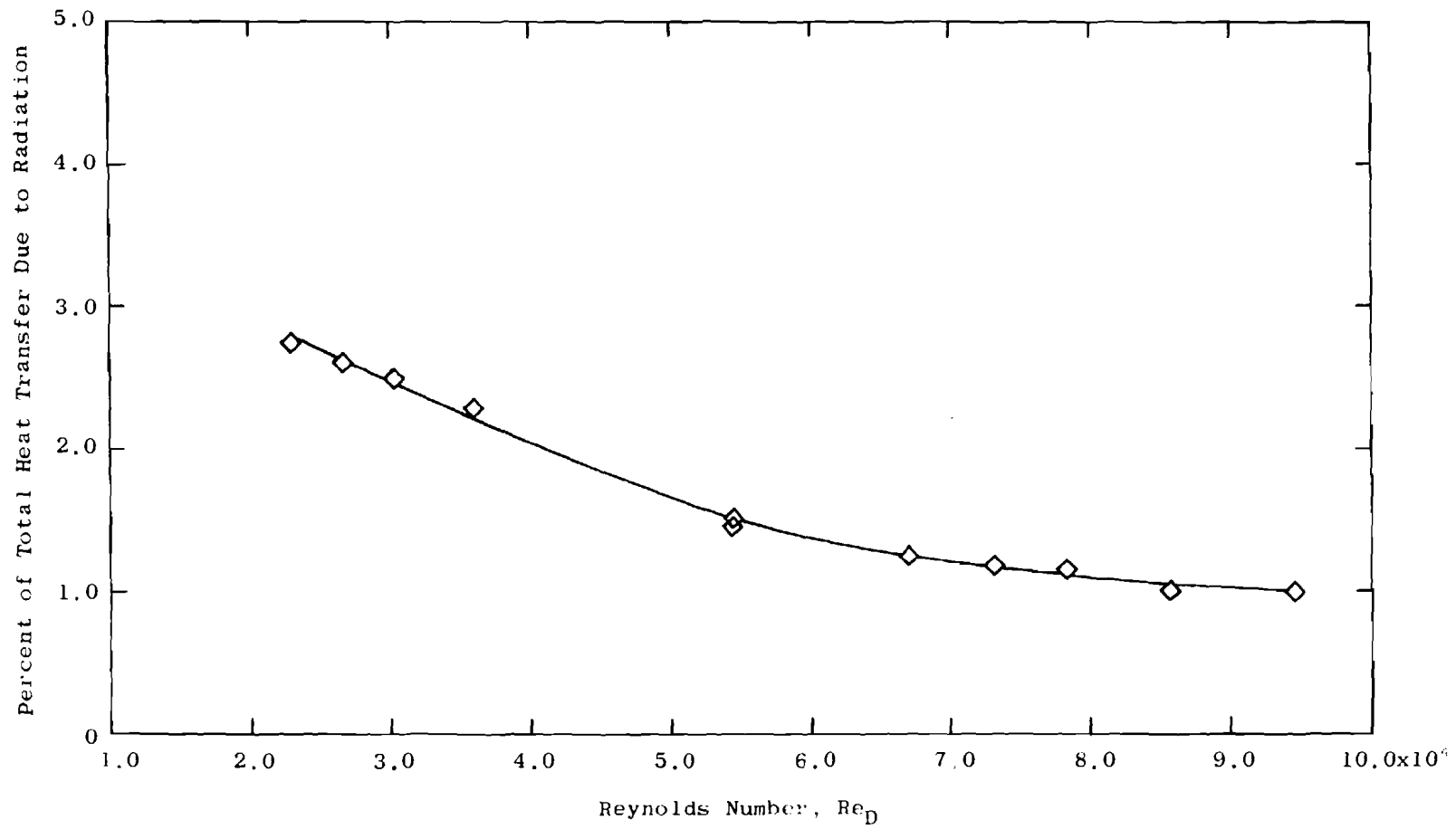


Fig. 14 Percentage of Total Heat Transfer Caused by Radiation for Air-Equivalent Mixture Tests, $T_b \approx 1050^\circ R$