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TECHNICAL NOTE 4156

EFFECT OF INITIAL MIXTURE-TEMPERATURE ON BURNING VELOCITY OF HYDROGEN-AIR MIXTURES WITH PREHEATING AND SIMULATED PREBURNING

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EFFECT OF INITIAL MIXTURE TEMPERATURE ON BURNING VELOCITY OF HYDROGEN-AIR MIXTURES WITH PREHEATING AND SIMULATED PREBURNING

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SUMMARY

The effect of initial temperatures from about 300° to 700° K on the laminar burning velocity of hydrogen-air mixtures was determined from schlieren photographs of open flames. The temperature was raised in two ways: (1) by preheating of the hydrogen-air mixtures and (2) by simulated adiabatic preburning of part of the hydrogen in air at 300° K so that initial temperatures of 600° and 700° K would be attained for the resulting mixtures of hydrogen, air, water vapor, and nitrogen.

The following empirical equations for burning velocity u were determined:

(1) For hydrogen-air mixtures, at initial temperatures with preheating T_o of 287° to 700° K: with 29.6 percent hydrogen (stoichiometric mixture), $u = 0.01011\ T_o^{1.721}$; with 45.0 percent hydrogen (maximum-burning-velocity mixture), $u = 0.09908\ T_o^{1.413}$.

(2) For mixtures of hydrogen, air, water vapor, and nitrogen, at initial temperatures with simulated preburning T_o of 300° to 700° K: with 29.6 percent hydrogen (original mixture), $u = 0.01145\ T_o^{1.695}$; with 45.0 percent hydrogen (original mixture), $u = 0.3829\ T_o^{1.175}$.

With 29.6 and 45.0 percent hydrogen (original mixture), mole-for-mole substitution of nitrogen for water vapor in the preburning experiments caused no discernible change in burning velocity.

INTRODUCTION

A correlation of the combustion properties of propane-air mixtures (ref. 1) has indicated that combustion of these mixtures should be made

easier by preheating but not by preburning. The question was raised as to whether similar behavior would be shown by a nonhydrocarbon fuel. Accordingly, the effects of preheating and preburning on the burning velocity of hydrogen-air mixtures were investigated at initial temperatures from about 300° to 700° K. The temperature was raised in two ways: (1) by preheating of the hydrogen-air mixture and (2) by simulated adiabatic preburning of part of the hydrogen in air. The principal difference between the two methods of raising the initial temperature is that preheating raises the total enthalpy and flame temperature of the mixture, whereas in preburning the total enthalpy and flame temperature remain constant. 4591

The burning velocities of the two types of mixtures were determined by the Bunsen burner technique (ref. 2, p. 459) with schlieren optics. The burner was heated by individually controlled lengths of resistance wire. Preburning was simulated by adding water vapor and nitrogen to the hydrogen-air mixtures in the proper amounts.

SYMBOLS

A	axial cross-sectional area of flame cone, cm^2
b,c	empirical constants, dimensionless
h	height of flame cone, cm
l	slant height or length of generating curve of flame cone, cm
M	molecular weight, g/g-mole
n	empirical exponent for temperature dependence, dimensionless
P	total pressure of mixture
Q	volumetric flow of mixture, cm^3/sec
R	gas constant, cal/(g-mole)(°K)
S	lateral surface area of flame cone, cm^2
T_o	initial temperature, °K
u	burning velocity, cm/sec

v_m mass burning rate, $g/(cm^2)(sec)$

ρ_o density of initial mixture, g/cm^3

φ equivalence ratio, fraction of stoichiometric fuel-oxygen ratio

EXPERIMENTAL PROCEDURE

Gases

The fuel used in this investigation was electrolytic hydrogen, stated to be 99.8 percent pure by the supplier. Prepurified nitrogen and tap water were used to prepare the preburned mixtures. Laboratory service air containing approximately 0.3 volume percent water was used.

Fuel-air ratio and flame temperature (table I) were calculated by the method and data of reference 3 on the basis of air containing 20.95 mole percent oxygen (ref. 3, p. 19) with the remainder considered to be nitrogen.

Metering System

A conventional flow system utilizing critical flow orifices (ref. 4) was used to meter the gases (hydrogen, air, and nitrogen) to the burner. Water vapor was introduced by bubbling the mixed gases through water thermostatically controlled to the desired temperature. A manually operated solenoid permitted rapid shutoff of fuel and flushing of the fuel line with nitrogen in the event of flashback.

Burner Tubes and Temperature Control

Two brass burner tubes were used. One had a 3.00-millimeter inside diameter and was water-jacketed. This tube was used for runs at 287° and 317° K. Its length-to-diameter ratio of about 150 ensured laminar flow. For the runs at higher temperature a 2.31-millimeter-inside-diameter tube was used that had a length-to-diameter ratio of about 80. This tube was wrapped with three individually controlled lengths of asbestos-covered heating wire to permit regulation of the wall and gas temperatures.

A bare-wire iron-constantan thermocouple was used to monitor gas temperatures axially at three stations between the port and a point about 7 inches down into the burner. The monitored gas temperatures were maintained within 15° F of one another.

The apparatus just described sufficed for the simple preheating experiments.

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Simulation of Preburned Mixtures

Experimentally, the initial temperature was raised by means of the resistance wire wrapped around the burner, but the gas compositions to be burned were varied to correspond to preheated and preburned mixtures. In an actual preburning process, part of the hydrogen is burned to completion in air at the reference or inlet temperature, for example, 300° K. Since the process is adiabatic, the heat evolved raises the resulting mixture of hydrogen, oxygen, nitrogen, and water vapor to what may be called an initial temperature with preburning. The compositions following the partial combustion between 300° K and 600° or 700° K were computed by the method of reference 3 (p. 3). These compositions are listed in table II as a function of hydrogen in the original mixture.

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To simulate a preburned mixture, a mixture of hydrogen, air, and nitrogen was saturated with water vapor at a suitable temperature and then heated to an initial temperature of 600° or 700° K. The percent water required at the given equivalence ratio and initial temperature with preburning (as shown in table II) was converted to partial pressure of aqueous vapor at this temperature and 1 atmosphere. The saturation temperature corresponding to this partial pressure (aqueous tension) was then obtained from reference 5. Thus, mixtures containing 3.68 percent water vapor at 600° K required a saturation temperature 82.0° F. Similarly, mixtures with 4.96 percent water vapor at 700° K required a saturation temperature of 91.4° F.

The apparatus used to prepare mixtures with simulated preburning is shown schematically in figure 1. The entering gas stream was broken up into fine bubbles by a fritted-glass disk with low pressure drop. The disk was submerged in tap water in a stainless steel flask. The water in the flask was held to within 0.1° F of the desired saturation temperature. The water-bath temperature and that of the wet gas emerging from the bath were kept above the saturation temperature to prevent condensation. Two traps prevented carryover of drops of water into the burner.

Optical System

A parallel light beam was generated by an air-cooled quartz mercury lamp and a Z-type schlieren system (ref. 2, p. 212). After being chopped by a horizontal knife edge advanced from above, the focused beam produced the schlieren image of the flame at a magnification of 2. A 35-millimeter camera without a lens was used to photograph the flames. Exposure time was 1/20 second.

Measurement of Burning Velocity

Burning velocities were determined from the schlieren negatives by the equation (ref. 6)

$$u = Q/S \tag{1}$$

The surface area S was determined by the approximate relation for cone-like surfaces of revolution (ref. 7)

$$S = \pi A l/h \tag{2}$$

RESULTS AND DISCUSSION

Effect of Simple Preheating on Burning Velocity

In figure 2 the burning velocities of the preheated hydrogen-air mixtures are plotted against volume percentage of hydrogen at several initial temperatures. The over-all range was 287° to 700° K. Stream Reynolds number based on burner diameter varied between about 600 and 1000. For each run the initial temperature was held constant to within 2 percent, while percent hydrogen was varied. The curves show a maximum burning velocity with about 45 percent hydrogen ($\varphi = 1.95$). This percentage is the same as that of reference 8 at room temperature and is the same as Passauer's value (ref. 9) in the temperature range 293° to 703° K. It compares well with 42 percent hydrogen at 298° K reported in reference 10. There is no significant dependence of this percentage on initial temperature.

The data were fitted by the least-squares method to the following empirical equations:

At $\varphi = 1.00$

$$u = 0.01011\ T_o^{1.721} \tag{3}$$

at $\varphi = 1.95$

$$u = 0.09908\ T_o^{1.413} \tag{4}$$

The curves corresponding to the least-squares burning velocities with preheating at the two equivalence ratios are plotted in figure 3 against initial temperature. Corresponding points from the curves in figure 2 are also shown. The least-squares curves reproduce the data to within 0.7 percent at $\varphi = 1.00$ and to within 1.5 percent at $\varphi = 1.95$.

Effect of Preburning on Burning Velocity

Burning velocities of hydrogen-air mixtures under conditions of simulated preburning were determined at initial temperatures of 600° and 700° K. At 600° K, gas temperatures varied to within the usual 2 percent before and after the flame was photographed. At 700° K, gas temperatures varied erratically. This variation may be taken as evidence of preflame reaction. (With such poor temperature control, the burning velocities showed large scatter.)

In order to minimize preflame reaction at 700° K, the burner was coated by soaking overnight in a 10-percent aqueous potassium chloride solution. Good temperature control was thus achieved. The reason for using a coating of potassium chloride was its reported ability to lower the concentration of hydrogen peroxide produced by the slow combustion of a flowing hydrogen-oxygen mixture (ref. 11). (Lewis and von Elbe (ref. 12) consider this fact as evidence that dissociation of hydrogen peroxide is the initiation step in the hydrogen-oxygen reaction.) Therefore, it was thought that potassium chloride would inhibit initiation of any possible preflame reaction in the burner tube. With the burner coated the burning velocities of mixtures preburned to 700° K showed only the usual amount of scatter and were generally 150 to 400 centimeters per second higher than the erratic data obtained at 700° K with the burner uncoated. A run was then made at 600° K for comparison with the previous run at the same temperature with the burner not coated (fig. 4(a)).

Figure 4 is a comparison of the burning velocities of mixtures with initial temperatures of 600° and 700° K. These data are plotted against percent hydrogen by volume in the original mixtures.

Figure 4 and unreported data obtained at 700° K with the burner not coated lead to the following conclusions:

(1) At initial temperatures of both 600° and 700° K preburned mixtures burn at least 10 percent slower than preheated mixtures at original hydrogen percentages greater than 40.

(2) For the preburned mixtures the potassium chloride coating produces a negligible difference in burning velocity at 600° K but a marked increase at 700° K.

(3) The burning velocities of preburned mixtures peak at about 39 percent hydrogen ($\varphi = 1.5$).

In figure 4 the abscissa is percent hydrogen in the original mixture before simulated preburning. Consequently, at any given percent hydrogen the final flame temperature and total enthalpy are the same for a mixture preburned to 600° or 700° K and a hydrogen-air mixture initially at 300° K. Of course, the final flame temperature and total enthalpy of a mixture preheated to, for example, 600° K, are higher than the flame temperature and enthalpy of the same mixture preburned to 600° K. With preburning, the mole fraction of oxygen is decreased, and the average molecular weight of the mixture is increased. With preheating, these two quantities are constant.

The following equations were determined for the burning velocity u of preburned mixtures of hydrogen, air, water vapor, and nitrogen at initial

temperatures $T_o = 300^\circ$ to 700° K: With 29.6 percent hydrogen (original mixture)

$$u = 0.01145\ T_o^{1.695}$$

with 45.0 percent hydrogen (original mixture)

$$u = 0.3829\ T_o^{1.175}$$

The burning velocities of the preburned mixtures may also be expressed in terms of the mole fraction of original hydrogen burned to completion in the preburning process, as shown in the following table:

Initial temperature with preburning, °K	Equivalence ratio, 1		Equivalence ratio, 1.95	
	Fraction of hydrogen burned	Burning velocity, cm/sec	Fraction of hydrogen burned	Burning velocity, cm/sec
300	0	183	0	313
600	.125	555	.083	697
700	.167	775	.110	843

Burning velocities with preheating were rechecked at several equivalence ratios after a few preburning runs with the burner coated with potassium chloride. The new data did not differ by more than 7 percent from corresponding values in figure 2.

Thus, with simple preheating in the range 300° to 700° K, and with preburning to 600° K, the potassium chloride coating had no measurable effect on burning velocity. On the other hand, with preburning to 700° K, the coating eliminated large data scatter and raised the burning velocities significantly above values obtained without the coating.

The results at 700° K suggest that the presence of appreciable amounts of water vapor is required to catalyze preflame reactions at an uncoated brass wall; the potassium chloride coating appears to poison the surface effectively. Similar large data scatter and reduced burning velocity have been observed with propane-air mixtures prereacted at 900° K (ref. 13).

Effect of Substituting Nitrogen for Water in Preburning Experiments

Two runs were made in which the water in the preburned mixture was replaced by nitrogen (1 mole nitrogen per mole water vapor). In the first run the percent original fuel was 45.0 percent, and in the second, 29.6

percent. In both runs the burning velocities were well within the experimental error of the burning velocities of preburned mixtures prepared in the usual manner. Since substitution of nitrogen for water vapor raises the flame temperature (e.g., by about 28° K at $T_o = 700°$ K and 45.0 percent fuel in the original mixture), the constancy of the burning velocities suggests that water has a mild chemical promoting effect on the flame reaction.

Additional support for the suggestion that water promotes the flame reaction was obtained from Jahn's burning velocities of hydrogen-air-nitrogen mixtures at room temperature at constant values of the molar ratio $O_2/(O_2 + N_2)$ of the air-nitrogen mixtures (ref. 2, p. 460). For the sake of comparison, Jahn's maximum burning velocities were adjusted to initial temperatures of 300°, 600°, and 700° K. The adjusted maximum burning velocities are 20 to 30 percent lower than the maximum burning velocities of preburned mixtures with corresponding molar ratios defined as $O_2/(O_2 + H_2O + N_2)$.

Comparison of Effect of Preheating on Burning Velocities of Hydrogen and Propane

Figure 5 is a plot of burning velocities relative to those at 300° K for propane-air (ref. 7) and hydrogen-air mixtures as a function of initial temperature with preheating at maximum-burning-velocity (fig. 5(a)) and stoichiometric (fig. 5(b)) equivalence ratios. Each curve may be expressed in the form

$$\frac{u}{u_{300° K}} = bT_o^n + c \tag{5}$$

Inspection of figure 5 shows that $n > 1$ for both fuels and is significantly greater for propane at the maximum burning velocity. This is a rough indication that the over-all activation energy of the flame reactions for propane-air mixtures is higher than for hydrogen-air mixtures. Likewise, n would probably be greater for other common hydrocarbons than for hydrogen, since propane combustion properties are similar to those of other saturated hydrocarbons.

Interpretation of Results in Terms of Mass Burning Rates

The burning velocities were converted into mass burning rates in order to compare the behavior of hydrogen-air mixtures with that of propane-air mixtures in the following two respects:

(1) Dependence of mass burning rates of preburned mixtures on initial temperature. Reference 1 predicts only slight dependence of mass burning rate on initial temperature for preburned propane-air mixtures. This prediction was based on a Semenov-type correlation of the burning velocities of preheated mixtures, which was then extended to preburned mixtures.

(2) Dependence of mass burning rates of preheated mixtures on percent fuel at constant flame temperature. Reference 14 shows the existence of a minimum mass burning rate for propane-air mixtures at $\varphi = 1$.

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The variation of mass burning rate with initial temperature (with both preheating and simulated preburning) can be seen from figure 6. If the initial temperature of a mixture is raised by preburning, the variation of mass burning rate with initial temperature is greater with 29.6 percent hydrogen in the original mixture than with 45.0 percent hydrogen in the original mixture. For example, raising the initial temperature from 300° to 600° K increases the mass burning rate by 62 percent with 29.6 percent fuel in the original mixture and by 14 percent with 45.0 percent fuel. The effect of temperature on mass burning rate can be related to the effects of temperature on normal burning velocity and on molecular weight as follows:

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$$v_m = u\rho_o$$

and

$$\rho_o = PM/RT_o$$

Since P/R is constant at atmospheric pressure,

$$v_m \propto uM/T_o \tag{6}$$

For the preheated mixtures, M is a constant at constant equivalence ratio. Calculations showed that for the preburned mixtures at constant equivalence ratio

$$M \propto T_o^{0.0326} \tag{7}$$

The significance of equation (6) is that if the burning velocity u varies as the first power of T_o, then the mass burning rate will be practically independent of T_o. The calculation of reference 14 suggests that the mass burning rate for preburned stoichiometric propane-air mixtures is indeed independent of T_o. On the other hand, combining equations (3), (6), and (7) shows that for preburned hydrogen-air mixtures with 29.6 percent hydrogen the mass burning rate varies as $T_o^{0.727}$. Similarly, with 45.0 percent hydrogen in the original mixture, the mass burning rate varies

as $T_o^{0.207}$. Thus, at either equivalence ratio the mass burning rate for preburned hydrogen-air mixtures definitely depends on temperature.

If water vapor exerts a slight chemical promoting effect on the hydrogen-air flame reaction, the demonstrated positive temperature exponent of the mass burning rate of preburned mixtures appears reasonable. Furthermore, according to the Semenov theory, if water and carbon dioxide are mere diluents in the propane-air flame (as assumed in ref. 1), the temperature exponent of the mass burning rate for preburned mixtures should be zero. Reference 13 presents data which suggest that water and carbon dioxide may even be inhibitors in the propane-air flame. Thus, it seems reasonable that the temperature exponent of the mass burning rate of preburned propane-air mixtures should not exceed zero.

These trends may be described more simply in terms of "ease of combustion" (ref. 1). Combustion is said to be made easier if the mass burning rate is increased and the quenching distance and minimum ignition energy are reduced. Combustion of propane-air mixtures should be made easier only by preheating, as indicated by the predicted behavior of all three combustion properties (ref. 1). For hydrogen-air flames with about 29.6 and 45.0 percent hydrogen in the original mixture, combustion is made easier by simulated preburning as well as by preheating, since the mass burning rate for simulated preburning is proportional to a power of T_o greater than zero.

If water vapor does exert a mild chemical promoting effect on the hydrogen-air flame reaction but acts as a diluent or inhibitor in the analogous propane flame reaction, the difference in behavior of hydrogen and propane and the data on the effect of nitrogen substitution appear reasonable.

Further comparison of hydrogen-air and propane-air mixtures can be made in terms of the mass burning rates of preheated mixtures at constant flame temperature. In reference 14 experimental mass burning rates of preheated propane-air mixtures are plotted against percent propane at constant flame temperature. The plot shows a minimum at $\varphi = 1$, which is said to be caused by a hydrocarbon-oxygen mechanism rather than a hydrocarbon - active-particle mechanism. Figure 7 is an analogous plot for preheated hydrogen-air mixtures at a flame temperature of 2400° K. (Similar plots can be made at other flame temperatures.) Since hydrogen-air mixtures also show a minimum mass burning rate at $\varphi = 1$, it is suggested that data for both hydrocarbon and hydrogen flames favor a fuel-oxygen mechanism rather than a fuel - active-particle mechanism.

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Discussion of Activation Energy Derived from Burning Velocity

An attempt was made to estimate the over-all or global activation energy of the flame reaction from the burning velocities of preheated hydrogen-air mixtures. The thermal bimolecular equation of Semenov (ref. 15) was used. In its final form, the equation was reduced to a function of initial and flame temperatures. Thus, the activation energy was expressed as the sum of derivatives of the burning velocity and temperature terms with respect to reciprocal flame temperature. The calculation gave the following results: (1) In general, the separate derivatives were not constant, except for very rich mixtures. This means that the activation energies obtained depended on temperature. (2) Systematic variation of reaction orders of fuel and oxygen, or of the temperature dependence of such factors as the thermal conductivity at flame conditions, failed to yield an activation energy independent of temperature. (3) Average activation energies were determined at several equivalence ratios. These varied with the equivalence ratio.

The computation leads to the conclusion that the Semenov theory almost demands that the separate derivatives be constant. It seems highly fortuitous that temperature-dependent derivatives would combine to give a temperature-independent activation energy at a given equivalence ratio. Furthermore, attempts to fit reaction orders or temperature dependence to transport properties merely change coefficients of the temperature derivatives. A possible reason for the inability of the Semenov theory to yield a unique activation energy for this flame may be that the temperature dependence of the preexponential terms is comparable to and opposite in sign to that of the exponential term.

SUMMARY OF RESULTS

An investigation of the effect of initial mixture temperature on the burning velocity of preheated and preburned hydrogen-air mixtures gave the following results:

1. It appears that the water produced in preburning chemically promotes the hydrogen-air reaction. The evidence for this is threefold: (a) In near-stoichiometric mixtures of hydrogen and air, combustion is made easier by either preburning or preheating. With a typical hydrocarbon fuel like propane, predictions indicated that only preheating makes combustion easier. (b) At equivalence ratios of 1.00 and 1.95, mole-for-mole substitution of nitrogen for water vapor in preburning experiments causes no change in burning velocity, even though nitrogen substitution raises the flame temperature. (c) At equal initial temperatures and equal molar ratios of $O_2/(O_2 + \text{diluent})$, the maximum burning velocities of hydrogen-air-nitrogen mixtures are 20 to 30 percent lower than the maximum burning velocities of preburned mixtures.

2. Application of the Semenov theory of flame propagation to the burning velocities of preheated hydrogen-air mixtures did not yield an activation energy independent of temperature.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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TABLE I. - CALCULATED EQUILIBRIUM FLAME TEMPERATURES OF HYDROGEN-AIR MIXTURES AT 1 ATMOSPHERE AND VARIOUS INITIAL TEMPERATURES

Mixture composition		Flame temperature, °K, at initial temperature of -			
Percent hydrogen	Equivalence ratio	300° K	500° K	600° K	700° K
25.0	0.792	2160	2297	2357	2410
26.3	.850	2240	2367	2422	2471
27.0	.880	2275	2403	2452	2495
28.7	.957	2355	2460	2502	2550
29.6	1.000	2382	2475	2522	2567
31.2	1.08	2402	2504	2550	2592
32.5	1.15	2385	2497	2547	2594
33.5	1.20	2376	2486	2536	2587
38.7	1.50	2252	2390	2452	2510
45.7	2.00	2065	2215	2290	2360
51.3	2.50	1900	2072	2147	2222
55.8	3.00	1775	1940	2025	2100

TABLE II. - COMPOSITION OF PREBURNED MIXTURES

Hydrogen in original mixture		Gas in preburned mixture, mole fraction							
		Initial temperature, 600° K				Initial temperature, 700° K			
Percent	Equivalence ratio	Water	Hydrogen	Oxygen	Nitrogen	Water	Hydrogen	Oxygen	Nitrogen
29.6	1.00	0.0369	0.2640	0.1319	0.5673	0.0497	0.2530	0.1265	0.5708
32.0	1.12	.0369	.2884	.1268	.5480	.0497	.2774	.1213	.5516
36.0	1.34	.0368	.3291	.1183	.5158	.0497	.3190	.1127	.5186
38.0	1.46	-----	-----	-----	-----	.0497	.3395	.1086	.5022
39.0	1.52	.0368	.3596	.1119	.4916	-----	-----	-----	-----
40.0	1.59	-----	-----	-----	-----	.0496	.3596	.1041	.4867
42.0	1.72	.0368	.3902	.1055	.4675	-----	-----	-----	-----
44.0	1.87	-----	-----	-----	-----	.0495	.4010	.0957	.4542
45.0	1.95	.0368	.4208	.0991	.4434	.0495	.4147	.0928	.4435
48.0	2.20	.0368	.4513	.0927	.4192	.0494	.4420	.0871	.4220
51.0	2.48	.0368	.4819	.0863	.3951	-----	-----	-----	-----

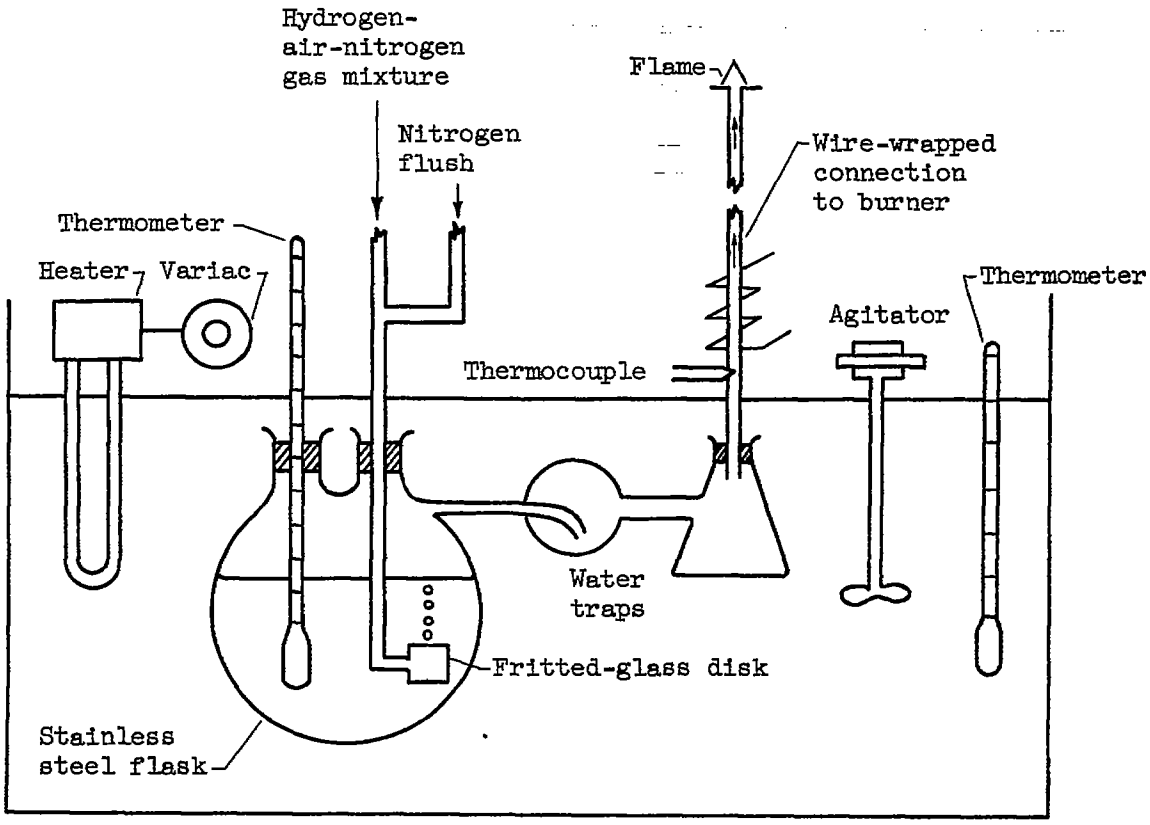

Figure 1. - Schematic diagram of apparatus for preparing mixtures with simulated preburning.

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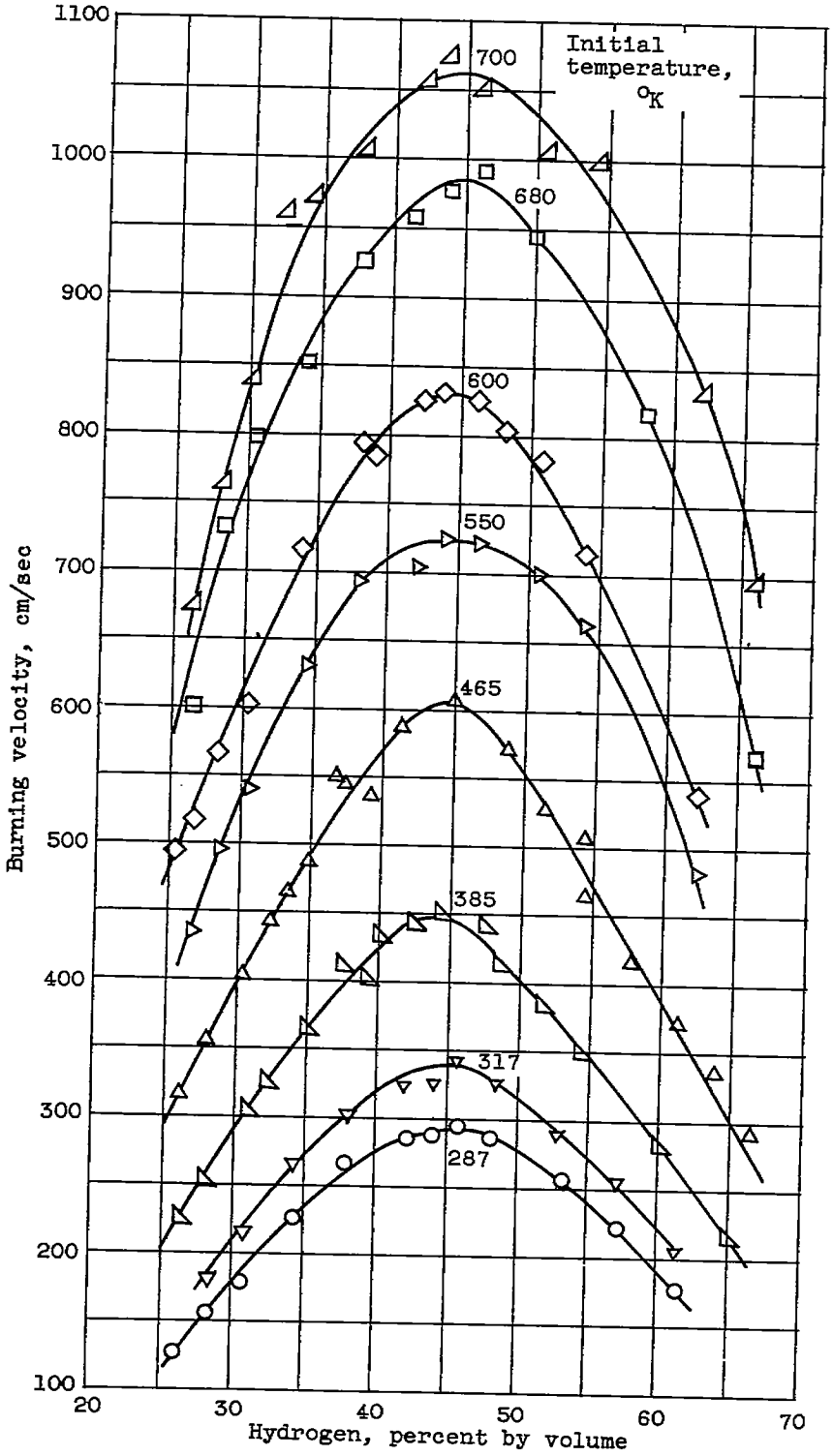

Figure 2. - Burning velocities of preheated hydrogen-air mixtures at various initial temperatures.

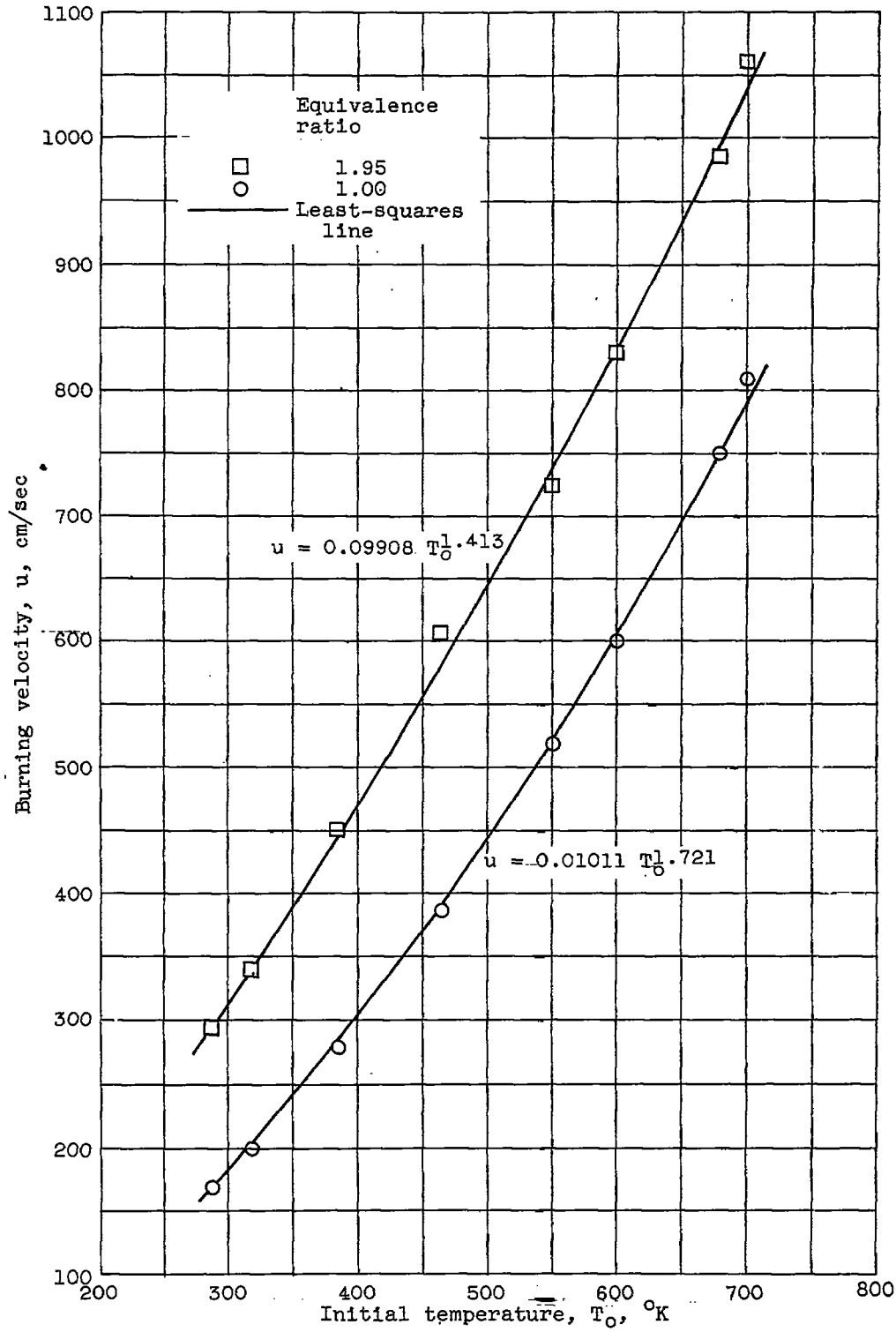

Figure 3. - Burning velocities of preheated hydrogen-air mixtures as function of initial temperature.

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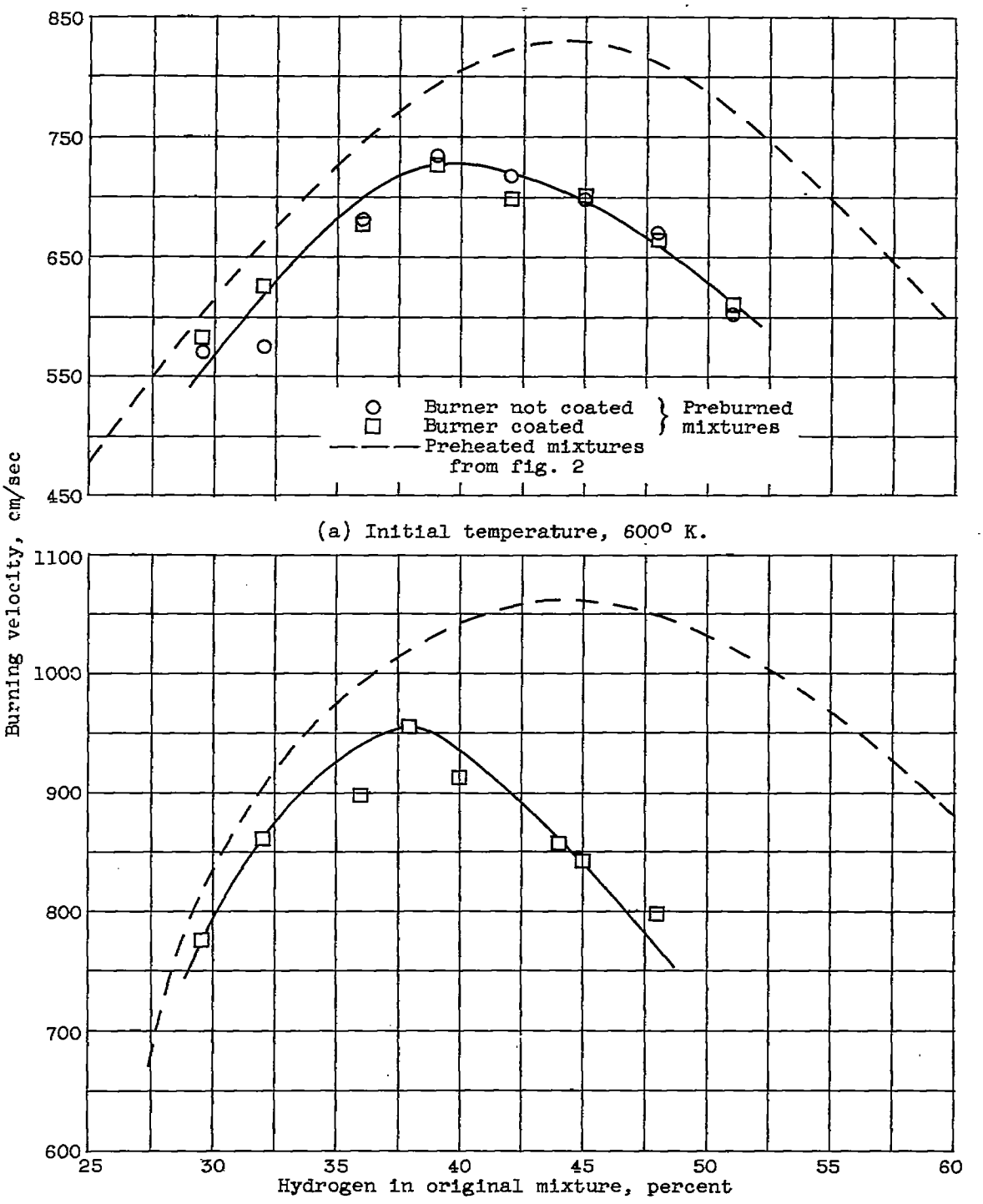

(a) Initial temperature, 600° K.

(b) Initial temperature, 700° K.

Figure 4. - Comparison of burning velocities of preheated and preburned hydrogen-air mixtures.

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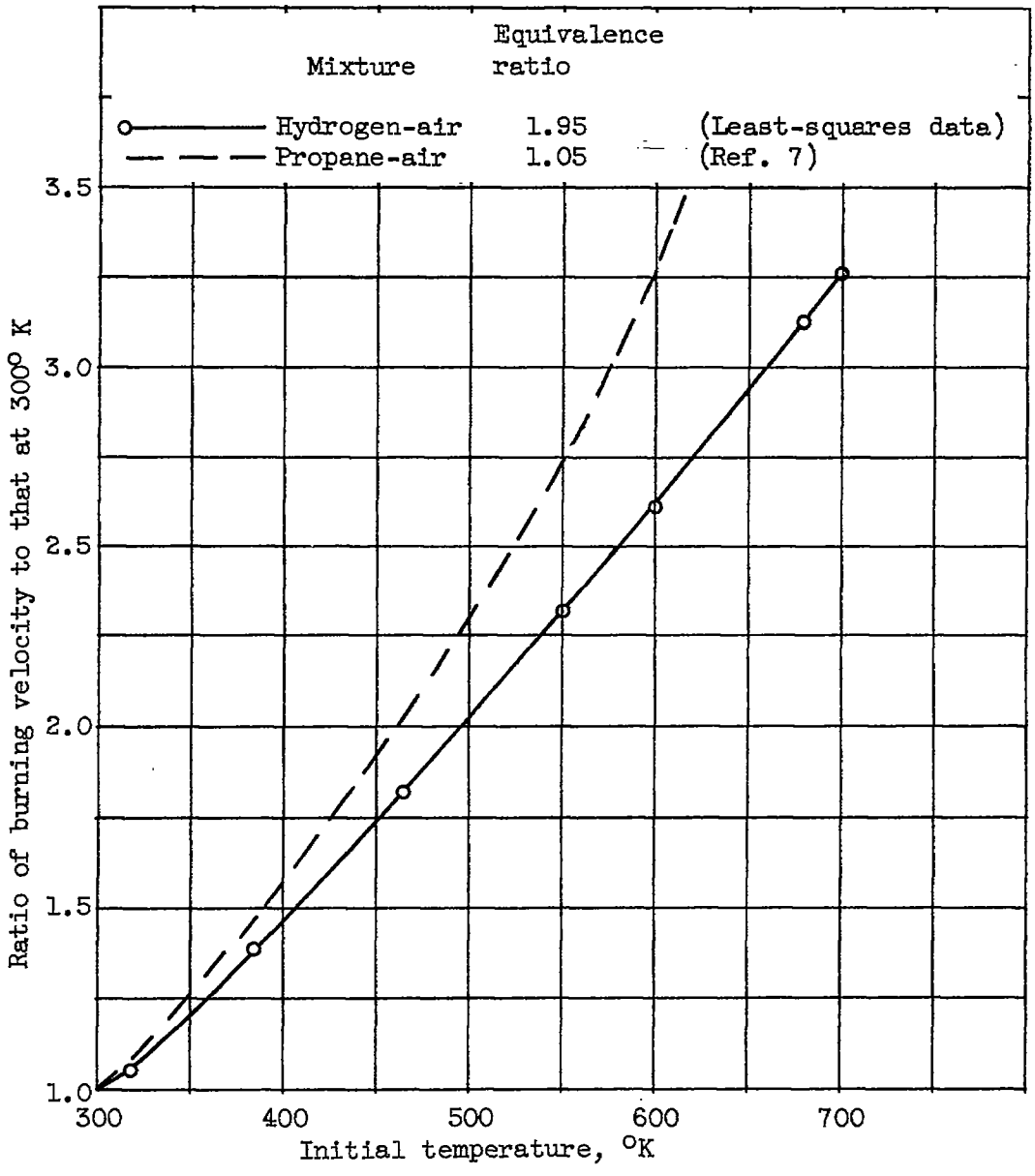
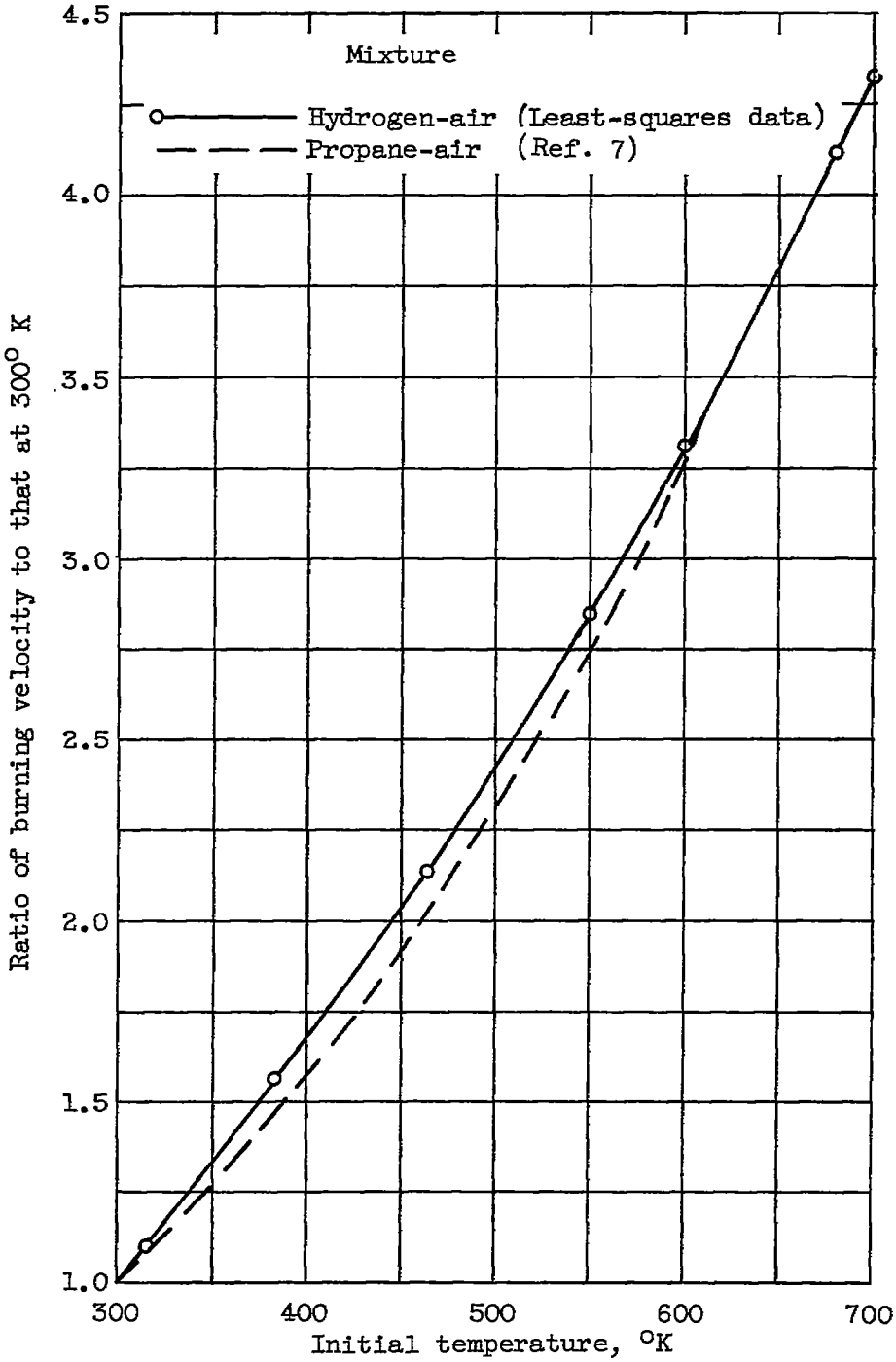


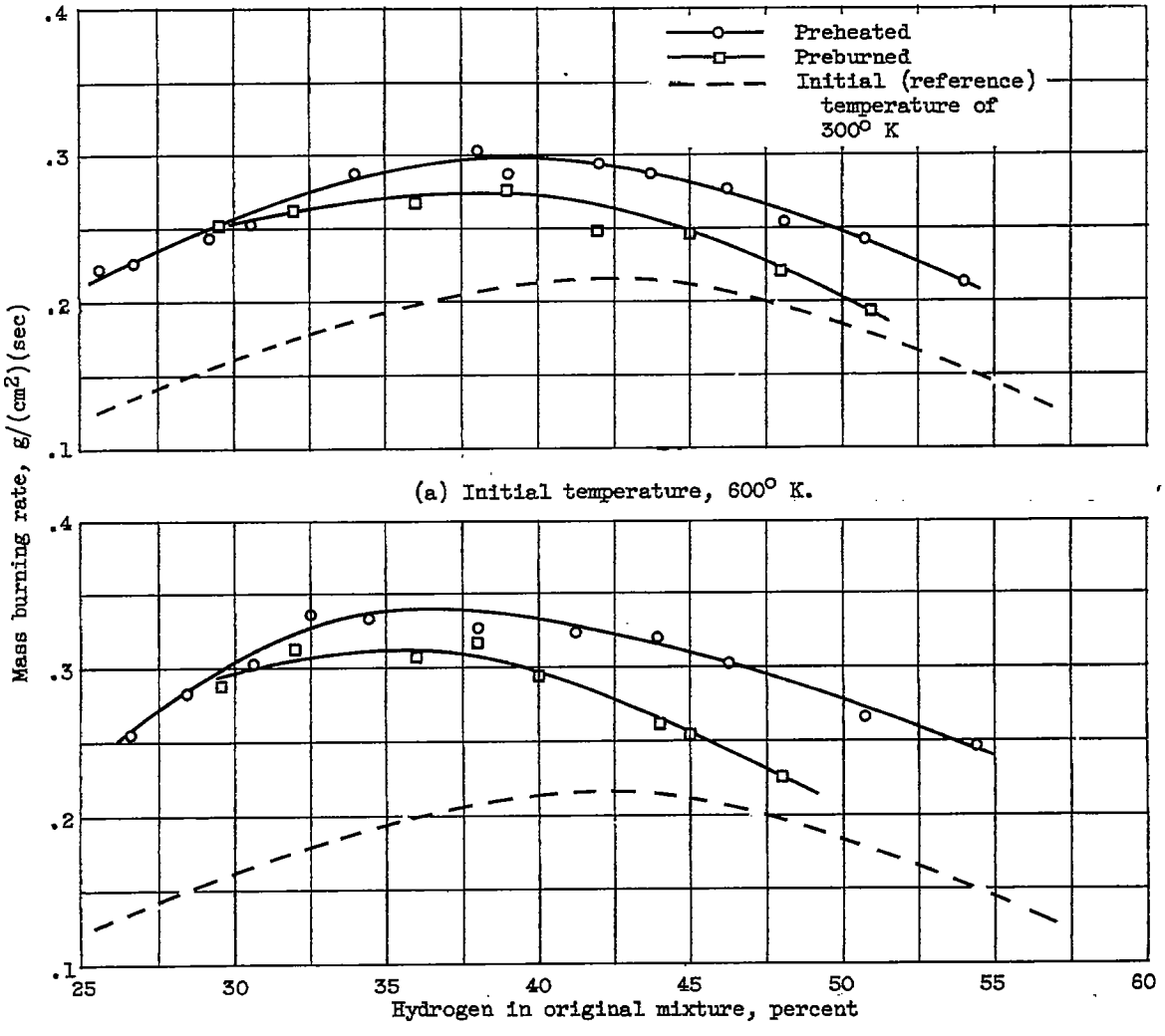
(a) Equivalence ratios corresponding to maximum burning velocity.

Figure 5. - Burning velocities of preheated hydrogen-air and propane-air mixtures as function of initial temperature.



(b) Stoichiometric equivalence ratio.

Figure 5. - Concluded. Burning velocities of preheated hydrogen-air and propane-air mixtures as function of initial temperature.



(a) Initial temperature, 600° K.

(b) Initial temperature, 700° K.

Figure 6. - Effect of initial mixture temperature on mass burning rate of preheated and preburned hydrogen-air mixtures.

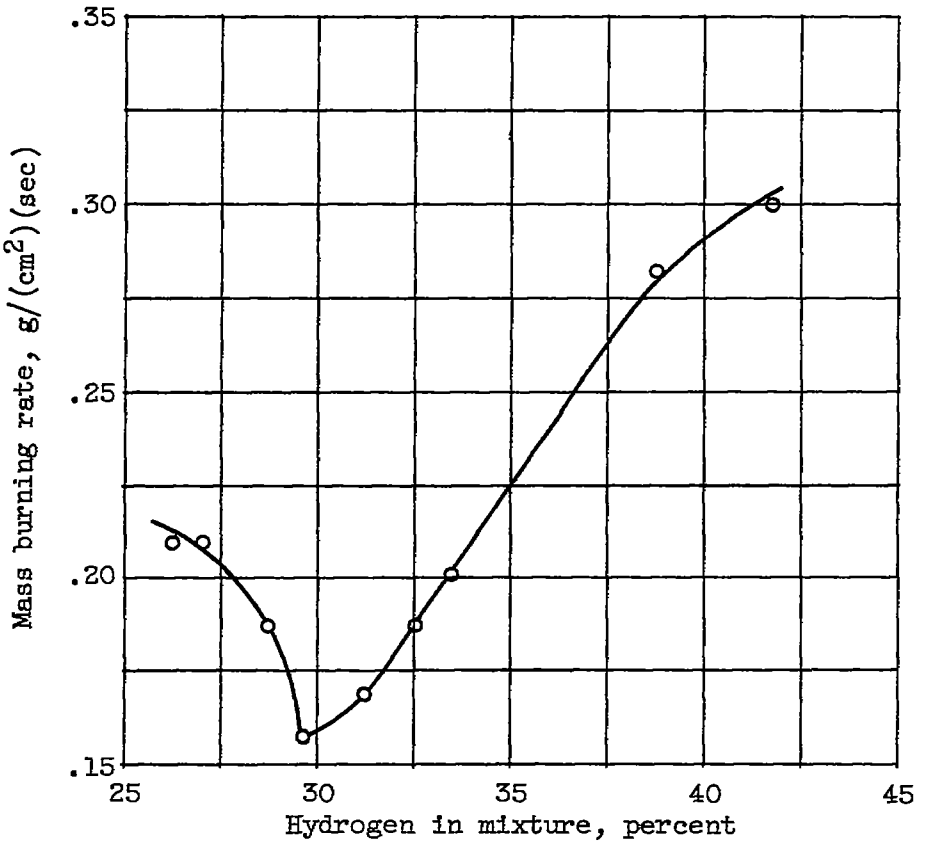


Figure 7. - Mass burning rate of preheated hydrogen-air mixtures as function of percent fuel. Adiabatic flame temperature, 2400° K.