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TECHNICAL NOTE 2170

EFFECT OF INITIAL MIXTURE TEMPERATURE ON FLAME SPEEDS AND BLOW-OFF LIMITS OF PROPANE - AIR FLAMES

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SUMMARY

The effect of initial mixture temperature on flame speeds in the laminar-flow region and on blow-off limits in both the laminar- and turbulent-flow regions was investigated for Bunsen type flames of propane and air. Flame speeds were determined at various mixture compositions at each of several temperatures from 85° to 650° F by measuring the area of the Bunsen cone from shadowgraphs.

Flame speed increased with temperature from 1.54 feet per second at 85° F to 5.25 feet per second at 650° F. The observed relative effect of temperature on flame speed was in good agreement with that predicted by the thermal theory as presented by Semenov, whereas the effect predicted by the square-root law of Tanford and Pease is as much as 35 percent lower than experimental results. Flame speed was independent of tube size from 3/8 to 7/8 inch or stream-flow Reynolds number from 1500 to 2100.

Blow-off limit data were obtained for the temperature range 90° to 650° F. The relation between mixture composition and velocity gradient at the tube wall at blow-off was dependent on the initial temperature.

INTRODUCTION

A knowledge of the effect of temperature on the normal burning velocity, called flame speed herein, and on the stability limits of fuel-air mixtures is necessary to the understanding of the combustion process and to certain applications of it, for example, in the future design of jet-engine combustors.

Theories of flame propagation predict that flame speed will increase with temperature at an increasing rate. Flame speed was found to be approximately proportional to the

square of the absolute temperature over the range from 32° to 1292° F for city-gas - air flames (reference 1). The data of Johnston (reference 2) on natural gas - air flames show a slight increase in the rate of change of flame speed with temperature from 137° to 902° F. Sachsse (reference 3) reports an increasing rate of change for methane-oxygen flames from 68° to 1832° F, although he found a linear relation between flame speed and temperature for propane-oxygen flames from 68° to 932° F. According to Broeze (reference 4), a linear relation exists for propane-air and butane-air flames from 68° to 392° F. 1350

Stability-limit data for mixtures at room temperature are correlated by boundary velocity gradient - composition plots, eliminating tube diameter as an independent parameter, in references 5 to 7. The effect of initial mixture temperature on blow-off limits is not included in these references.

The investigation of the effect of inlet mixture temperature on flame speeds and blow-off limits reported herein was conducted at the NACA Lewis laboratory as part of a fundamental combustion research program. The investigation consisted of a study of flame speed and blow-off limit as functions of mixture composition at several different temperatures for Bunsen type flames of propane and air. A comparison of the flame-speed data with relative values predicted by both a thermal and a diffusion theory is reported.

APPARATUS AND INSTRUMENTATION

The apparatus used in this investigation is diagrammatically illustrated in figure 1. The fuel used was commercial propane with a minimum purity of 95 percent; the principal impurities were ethane and isobutane. Laboratory service air containing approximately 0.3-percent water by weight was used. Propane and air were separately metered, mixed, preheated, and burned above a vertical tube.

The burner tubes used were 5-foot lengths of brass or stainless-steel tubing having inside diameters of 3/8, 5/8, and 7/8 inch. The preheating section was a 5-foot length of 3/8-inch inside-diameter stainless-steel tubing connected to the base of the burner tube. Both the preheater and the burner tube were wrapped with resistance wire; the burner tube was wrapped to prevent heat loss from the heated gases to the burner-tube wall. The preheater-burner assembly was insulated with magnesia pipe covering. A 3-inch-diameter collar was soldered to the lip of each burner tube to give a flat horizontal lip above the insulation. A Lucite draft shield was placed around the burner port.

The propane and air flows were metered by two sets of critical-flow orifices (reference 8). Ruby jewel bearings of appropriate sizes were used as the orifice plates. Each set of orifices consisted of six jewel bearings with different orifice diameters installed in parallel in a manifold. For each orifice, when measuring the upstream pressure with a 100-inch mercury manometer, the ratio of the highest available flow rate to the lowest was 2:1; with six orifices in parallel a 64-fold increase over the lowest flow rate was obtained. A flexible hose was used to connect the downstream end of the orifice in use to the mixing section; the other five orifices were capped. The orifices were calibrated in place using wet test meters.

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Temperatures were measured by iron-constantan thermocouples installed at the inlet to each orifice manifold and at the burner-tube inlet and port for both wall and gas temperatures. The thermocouple for measuring the gas temperature at the port was an aspirating couple in a bolt-action sliding probe.

A 25-watt concentrated-arc lamp was used as the light source for the shadowgraph system, which is schematically shown above the burner port in figure 1.

EXPERIMENTAL PROCEDURES

The desired fuel and air flows were set by adjusting the pressure regulators; the gas mixture was brought to the desired temperature at the burner port; and the tube wall was maintained at the same temperature $\pm 20^{\circ}$ F by varying the inputs to the resistance wires. When the desired temperature was obtained, the thermocouple probe was withdrawn and the mixture was ignited at the burner port.

For flame-speed determinations, a shadowgraph was made, the flame was extinguished, and the gas-stream temperature at the port and flow-rate settings on the manometers were rechecked. In determining a blow-off point, the mixture was enriched enough to obtain ignition and then the fuel rate reduced until the flame just blew off the burner. Temperature and flow-rate readings were then taken.

METHODS OF CALCULATION

Flame speeds were determined from the shadowgraphs by the total-area method, wherein the average normal flame speed is equal

to the volume rate of flow of the unburned mixture divided by the surface area of the cone formed by the combustion zone. This surface area S was determined by the approximate relation for cone-like surfaces of revolution 1350

$$S = \pi A l/h \tag{1}$$

where

A longitudinal area of cone as outlined by demarkation between black and white in shadowgraph, (sq ft)

l slant height or length of generating curve, (ft)

h height of cone, (ft)

Velocity gradients at the tube wall for blow-off at a given mixture composition were computed by the relations (based on equations given in references 5 and 7):

For laminar flow, $Re < 2100$

$$g_l = \frac{8\bar{u}}{d}$$

For turbulent flow, $N_{Re} > 3000$

$$g_t = \frac{0.040\ \bar{u}^2 \rho}{Re^{0.25}\mu}$$

For transition region, $2100 < Re < 3000$

$$g_T = \frac{f\ \bar{u}^2 \rho}{2\mu}$$

where

d tube diameter, (ft)

f friction factor estimated from curve given by McAdams (reference 9, p. 118)

g velocity gradient at tube wall, (ft/(sec)(ft))

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Re Reynolds number of stream flow

$\bar{u}$ average stream velocity, (ft/sec)

μ stream viscosity, (lb/(sec)(ft))

ρ stream density, (lb/ft^3)

Subscripts:

l laminar flow

T transition region

t turbulent flow

RESULTS

Laminar Flame Speeds

The flame-speed data obtained with the 5/8-inch stainless-steel tube at two stream-flow Reynolds numbers of 1500 and 2100 are plotted in figure 2 as flame speed against percentage propane by volume at each of six temperatures: 85°, 200°, 300°, 400°, 500°, and 650° F. Each of the curves shows the maximum flame speed for a given temperature to occur at a mixture composition slightly richer than stoichiometric.

Flame-speed measurements based on the area of the shadowgraph of the Bunsen cone are more nearly absolute values than measurements based on the area of the luminous flame cone because the measurements based on the area of the shadowgraph of the Bunsen cone give good agreement with the values obtained by the stroboscopically illuminated - particle method (reference 10). The value of 1.54 feet per second at 85° F for propane and air reported herein is in agreement with values of 1.49 and 1.48 feet per second at room temperature obtained by the shadowgraph and illuminated particle methods, respectively, (reference 10). The data of figure 2 show that a change in stream-flow Reynolds number from 1500 to 2100 produced no measurable effect on flame speed. Preliminary data obtained with 3/8-, 5/8-, and 7/8-inch brass tubes by photographing the luminous flame cone showed the tube diameter to have little effect on laminar flame speed. A few comparative values are given in table I. By comparison of table I with curve AB of figure 3, it can be seen

that values of flame speed based on the area of the luminous cone are approximately 20 percent lower than those based on the area of the shadow cone.

The flame-speed maximums from the curves of figure 2 are plotted against temperature to give curve AB in figure 3. The flame speed increases with increase in temperature, from 1.54 feet per second at 85° F to 5.25 feet per second at 650° F. The rate of increase of flame speed increases with temperature. 1350

Blow-off Limits

Blow-off limit data at 90°, 300°, 450°, and 650° F are plotted as percentage propane by volume against stream velocity in figure 4(a). The same data are plotted as percentage propane by volume against velocity gradient at the tube wall in figure 4(b). The composition - velocity-gradient plot gave a single correlation line for blow-off data obtained with different tube diameters at the same temperature, as was found by other investigators (references 5 to 7). Velocity gradient at blow-off increased with increasing temperature (increasing flame speed) for a given fuel-air mixture.

DISCUSSION OF RESULTS

Two proposed mechanisms for the propagation of flame are considered: One is based primarily on the conduction of heat from the combustion zone into the unburned gases and the other is based on the diffusion of active radicals from the combustion zone into the unburned gases. Both of these theories are used to predict the relative effect of temperature on flame speed.

In considering a thermal theory, it has been pointed out that early heat theories (for example, reference 11, p. 113, and reference 12), which assumed that (a) reaction begins at the self-ignition temperature, and that (b) the reaction rate is constant between the self-ignition temperature and the flame temperature, are inadequate. The concept of ignition temperature has no meaning apart from an autoignition experiment, which requires a certain induction period. Actually, reaction rate continuously increases with temperature because it is a function of

$$\exp(-E/RT)$$

where

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exp base of Napierian logarithmic system raised to power in parenthesis following exp

E activation energy, (Btu/lb-mole)

R universal gas constant, (Btu/(lb-mole)($^{\circ}$R))

T absolute temperature, ($^{\circ}$R)

Semenov (reference 12) derived an approximate equation that involves only the initial mixture temperature, flame temperature, and physical properties at these temperatures. If the controlling step is a bimolecular reaction, the appropriate final equation is

$$u = \sqrt{\frac{2\lambda_f k a_0 c_{p,f}^2}{\rho_0 \overline{c_p}^3} \left(\frac{T_0}{T_f}\right)^2 \left(\frac{\lambda}{c_p \rho D}\right)_f^2 \left(\frac{n_1}{n_2}\right)^2 \left(\frac{RT_f^2}{E}\right)^3 \frac{\exp(-E/RT_f)}{(T_f - T_0)^3}} \qquad (2)$$

where

a_0 number of molecules per unit volume of combustible in initial mixture

c_p specific heat, (Btu/(lb)($^{\circ}$R))

$\overline{c_p}$ mean specific heat, T_0 to T_f, (Btu/(lb)($^{\circ}$R))

D diffusion coefficient, (ft^2/sec)

k constant from reaction-rate equation

n_1/n_2 moles of reactants per moles of products from stoichiometric equation

T absolute temperature, ($^{\circ}$R)

u flame speed, (ft/sec)

λ thermal conductivity, (Btu/(ft^2)(sec)(ft))

ρ density of mixture, (lb/ft^3)

Subscripts:

f property at flame temperature

0 property at initial temperature

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Equation (2) takes into account the cases where (a) specific heat and thermal conductivity vary with temperature, (b) the number of molecules changes during reaction, and (c) the diffusion coefficient D_f does not equal the coefficient of temperature conductivity $(\lambda/c_p \rho)_f$. Case (c) means that although the sum of the thermal and chemical energies will be the same for the over-all process, the sum of the energies will vary within the combustion zone. For example, if $D_f > (\lambda/c_p \rho)_f$, the thermal energy supplied by heat conduction upstream of the flame zone will be less than the chemical energy conducted away by diffusion. Thus, diffusion enters only as it affects the energy balance.

By eliminating from equation (2) the terms independent of temperature, by substituting, as approximate relations for the temperature-dependent terms, those relations determined for air, and by combining terms, the equation reduces to the form

$$u \propto \sqrt{T_0^2 T_f^{4.9} \frac{\exp(-E/RT_f)}{(T_f - T_0)^3}} \tag{3}$$

(Physical properties for air were estimated from reference 9, pp. 391-411 and related to temperature as follows: $\lambda \propto T^{0.84}$; $c_{p,f} \propto T^{0.09}$; $\overline{c_p} \propto T^{0.09}$; $D \propto \mu/\rho \propto T^{1.67}$, where μ is viscosity; $\rho \propto T^{-1}$; and $a_0 \propto T^{-1}$.) This reduced form of the equation may be used to estimate the relative effect of temperature on flame speed (thermal theory) for hydrocarbons burning with air, provided that the relations between the physical properties and the temperature for the mixture are reasonably near those for air.

A diffusion mechanism of flame propagation may also be considered for the prediction of the effect of temperature on flame speed. For moist carbon monoxide - air flames, the flame speed correlates well with the equilibrium hydrogen-atom concentration, but not with hydroxyl-radical or oxygen-atom concentration (references 13 and 14). This correlation led Tanford and Pease to propose

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that the rate of diffusion of hydrogen atoms upstream of the flame front determines the rate of flame propagation. This concept, generalized to include other radicals, which might be important for other systems, is expressed by what has been called the square-root law of burning velocity (reference 14):

$$u = \sqrt{\sum_i p_i D_i k_i L \frac{Q'}{QB_i}} \tag{4}$$

where

B_i term near 1 arising from radical recombination

D_i coefficient of diffusion of radical into unburned gas

k_i rate constant for its interaction with combustible material

L number of molecules per unit volume of gas at some mean temperature

Q mole fraction of potential combustible product in unburned gas

Q' mole fraction of combustible in unburned gas

p_i mole fraction or partial pressure of given radical in burned gas

Equation (4) is an approximate solution of the expression obtained for the rate of product formation.

If a correlation exists between the flame speed of a hydrocarbon-air mixture and its equilibrium radical concentrations, the relative effect of temperature on flame speed could be estimated by the square-root law. If it is assumed that only p_i, D_i, and L are appreciably temperature dependent, the square-root law will reduce to

$$u \propto \sqrt{\left(\sum_i p_i D_{i,r}\right) T_0^{1.67} T_{av}^{-1}} \tag{5}$$

($D_i \propto D_{i,r} T_0^{1.67}$, where $D_{i,r}$ is the relative diffusion coefficient of the given radical with respect to the other radicals; $L \propto T_{av}^{-1}$, where $T_{av} = (T_0 + T_f)/2$.)

A comparison of the relative effect of initial temperature on flame speed predicted by the reduced equations (3) and (5) is presented in figure 3. The experimental value of 1.54 feet per second at 85° F was used as the basis for computation of relative values at higher temperatures by these expressions. For computation of these relative values for the curves in figure 3, the following values and approximations were used: 1350

$E = 68{,}000$ (Btu/lb-mole) (reference 11, p. 437)

$\Delta T_f = 0.45\ \Delta T_0$ (from theoretical flame-temperature calculations, where ΔT_f is change in flame temperature resulting from change in initial temperature ΔT_0)

$T_f \cong 3960^\circ$ R for $T_0 \cong 550^\circ$ R (based on sodium D-line measurement, reference 15)

The equilibrium partial pressures of hydrogen atoms p_H, hydroxyl radicals p_{OH}, and oxygen atoms p_O for a mixture that contained 4.2-percent propane by volume were calculated by the graphical method of reference 16 and are presented in table II. The desired values for curves AD and AE were obtained by logarithmic interpolation from table II. Curve AD is based upon

$$\sum_i p_i D_{i,r} = 6.5\ p_H + p_{OH} + p_O$$

because the diffusion rate for hydrogen atoms is roughly 6.5 times that for the other radicals. Curve AE is based on the hydrogen-atom concentration alone and falls upon curve AD within the accuracy of the calculations.

The curves in figure 3 show that the relative effect of temperature on flame speed predicted by the thermal theory agrees satisfactorily with experimental results; whereas that predicted by the diffusion theory is up to 35 percent lower. The effects of using different values of T_f, ΔT_f, and E were checked and found to be as follows:

(1) Increasing T_f from the measured temperature of 3960° R to the theoretical temperature of 4300° R at $T_0 = 550^\circ$ R (reference 15)

resulted in predictions of the relative increases in flame speed at 650° F that were 5 percent low for the thermal theory and 35 percent low for the diffusion theory.

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(2) Using $\Delta T_f = 0.50\ T_0$ rather than $0.45\ T_0$ gave increases at 650° F that were 12 percent high for the thermal theory and 32 percent low for the diffusion theory.

(3) Using $E = 45{,}000$ instead of 68,000 Btu per pound-mole gave an increase at 650° F that was 5 percent low for the thermal theory.

(4) Combining steps (1) and (3) gave an increase that was 17 percent low for the thermal theory.

If the terms B_i in equation (4) were greater than 1 (references 13 and 14), the values for the diffusion-theory curve would be even lower. Both theories predict that flame speed will increase with temperature at an increasing rate.

Other calculations, not given here, indicate that the data of reference 4 for propane - air flames at concentrations near stoichiometric would give similar relations between observed values and values predicted by the theories on the relative basis. Data given in reference 2 on natural gas - air flames and acetylene - air flames also appear to be in fair agreement with relative values predicted by the thermal theory, whereas relative values predicted by the diffusion theory are lower.

The square-root law does not appear to predict the experimental results for these hydrocarbon-air flames as well as the thermal theory does, but it does not necessarily follow that the diffusion of active radicals is unimportant, nor does it mean that some other relation based on diffusion might not predict the experimental results. The calculated equilibrium radical concentrations would not correspond to the true radical concentrations if (a) equilibrium is not attained, (b) any appreciable reaction takes place at the initial temperature, or (c) there is a large chain-branching term affecting the radical distribution in and ahead of the flame zone (reference 14).

SUMMARY OF RESULTS

An investigation of the effect of initial mixture temperature on flame speeds in the laminar-flow region and on blow-off limits

in both the laminar- and turbulent-flow regions for Bunsen type flames of propane and air gave the following results:

1. The flame speed of propane-air mixtures increased from 1.54 feet per second at 85° F to 5.25 feet per second at 650° F. The rate of increase of flame speed increased with temperature. The results were independent of tube diameter from 3/8 to 7/8 inch and Reynolds number from 1500 to 2100. 1350

2. Approximate calculations indicated that both the thermal theory as presented by Semenov (for bimolecular reactions) and the diffusion theory of Tanford and Pease predict that flame speed will increase with temperature at an increasing rate. Relative increases in flame speed predicted by the thermal theory were in satisfactory agreement with experimental results, whereas those predicted by the square-root law (diffusion theory) were as much as 35 percent lower at the high temperatures. The square-root law yielded approximately the same results whether based on the hydrogen-atom concentration alone or on the summation of the effective relative concentrations of hydrogen atoms, hydroxyl radicals, and oxygen atoms.

3. The velocity gradient at the tube wall for blow-off increased with increasing temperature (increasing flame speed) for a given fuel-air mixture.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 8, 1950.

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TABLE I - COMPARISON OF FLAME-SPEED VALUES

OBTAINED WITH VARIOUS TUBE DIAMETERS

Initial temperature (°F)	Tube diameter (in.)	Maximum flame speed (luminous cone) (ft/sec)
90	3/8	1.25
	5/8	1.28
	7/8	1.28
300	3/8	2.26
	5/8	2.23
	7/8	2.33
400	3/8	2.72
	5/8	2.68
	7/8	2.72

TABLE II - PARTIAL PRESSURES OF ACTIVE

RADICALS AT THERMAL EQUILIBRIUM

Temperature (°R)	p_H (atm × 10^3)	p_{OH} (atm × 10^3)	p_O (atm × 10^3)
3960	0.43	1.62	0.087
4140	.77	2.9	.25
4320	1.35	5.2	.70

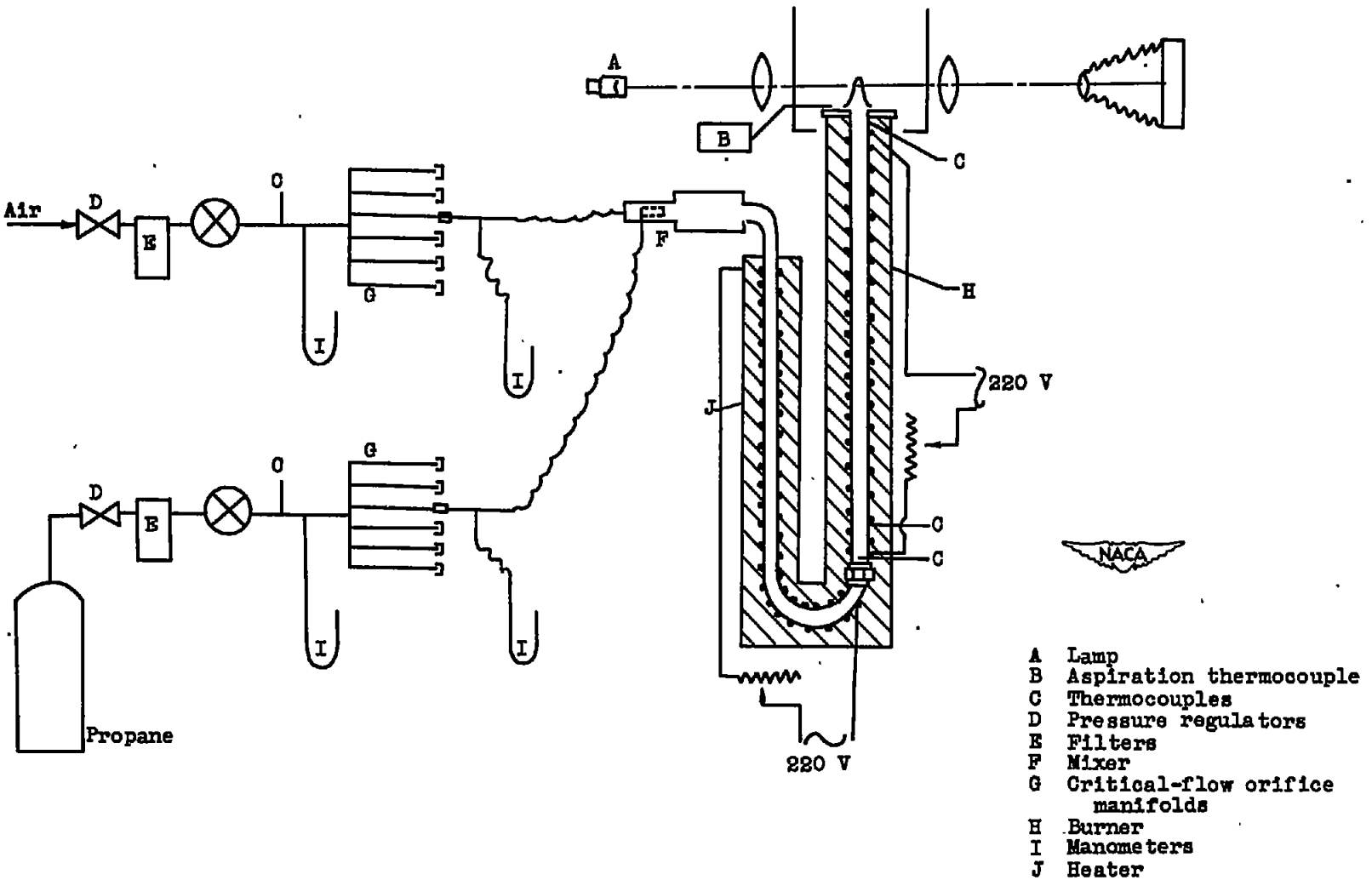


Figure 1. - Diagrammatic sketch of experimental apparatus.

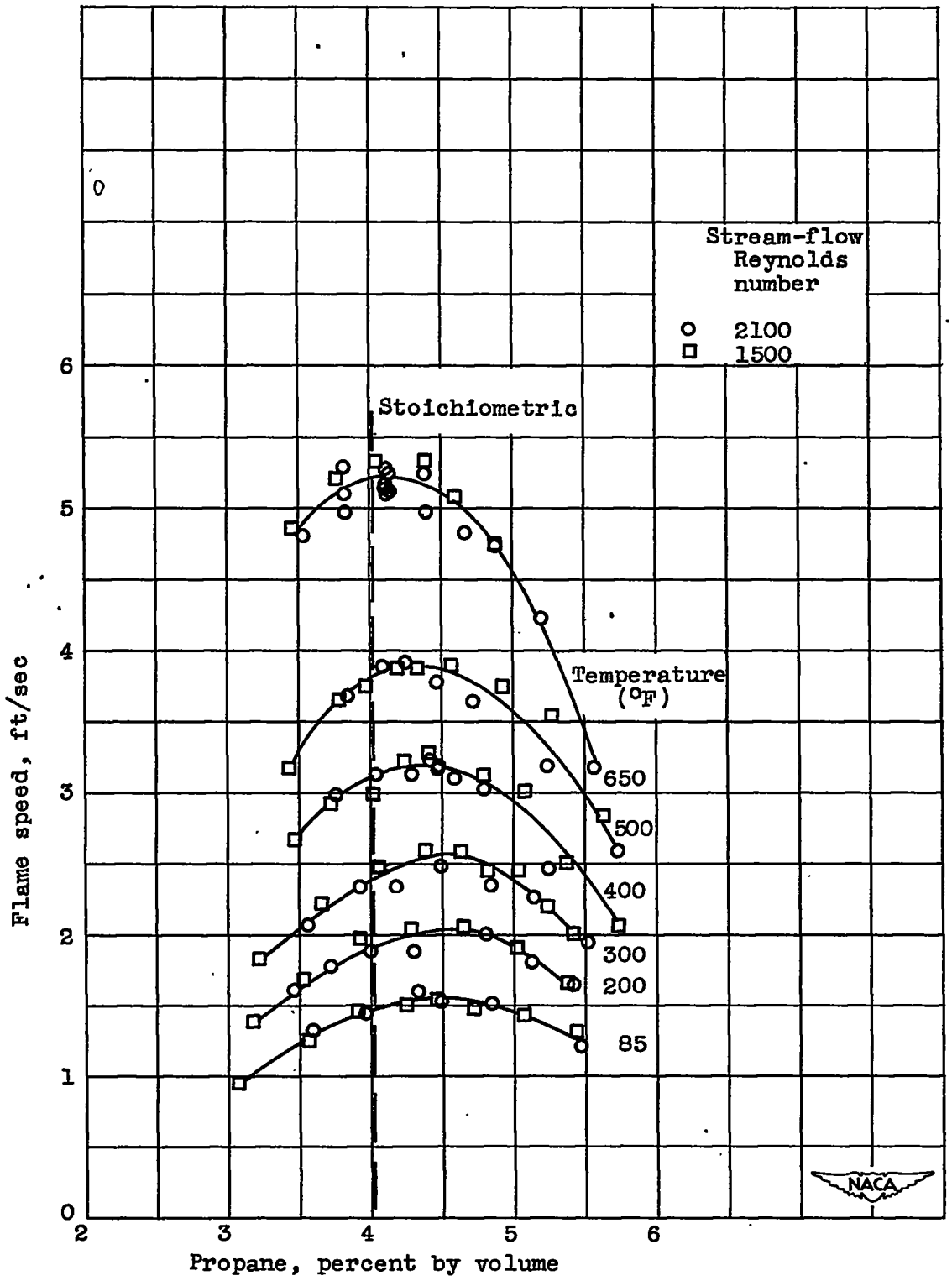


Figure 2. - Flame speed as function of percentage propane by volume at various temperatures. Stainless-steel-tube diameter, 5/8 inch.

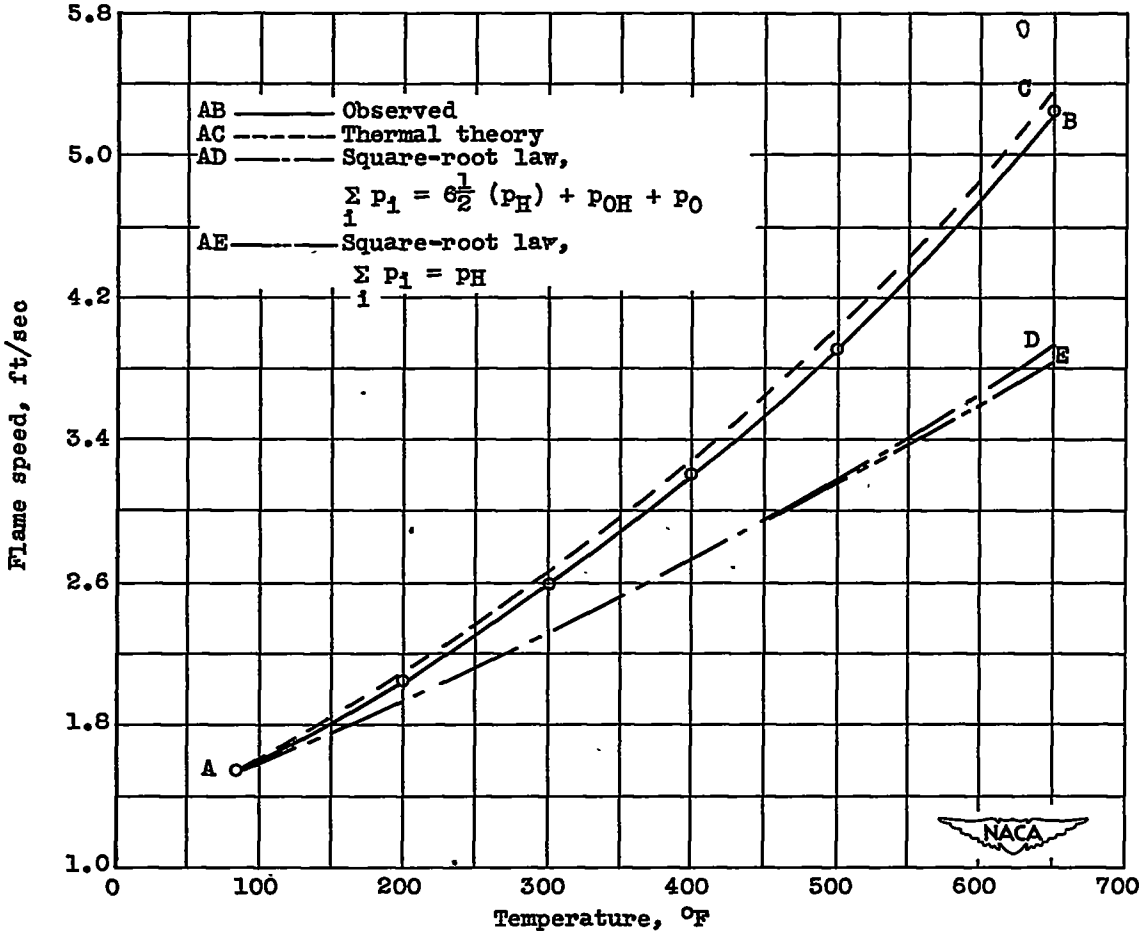
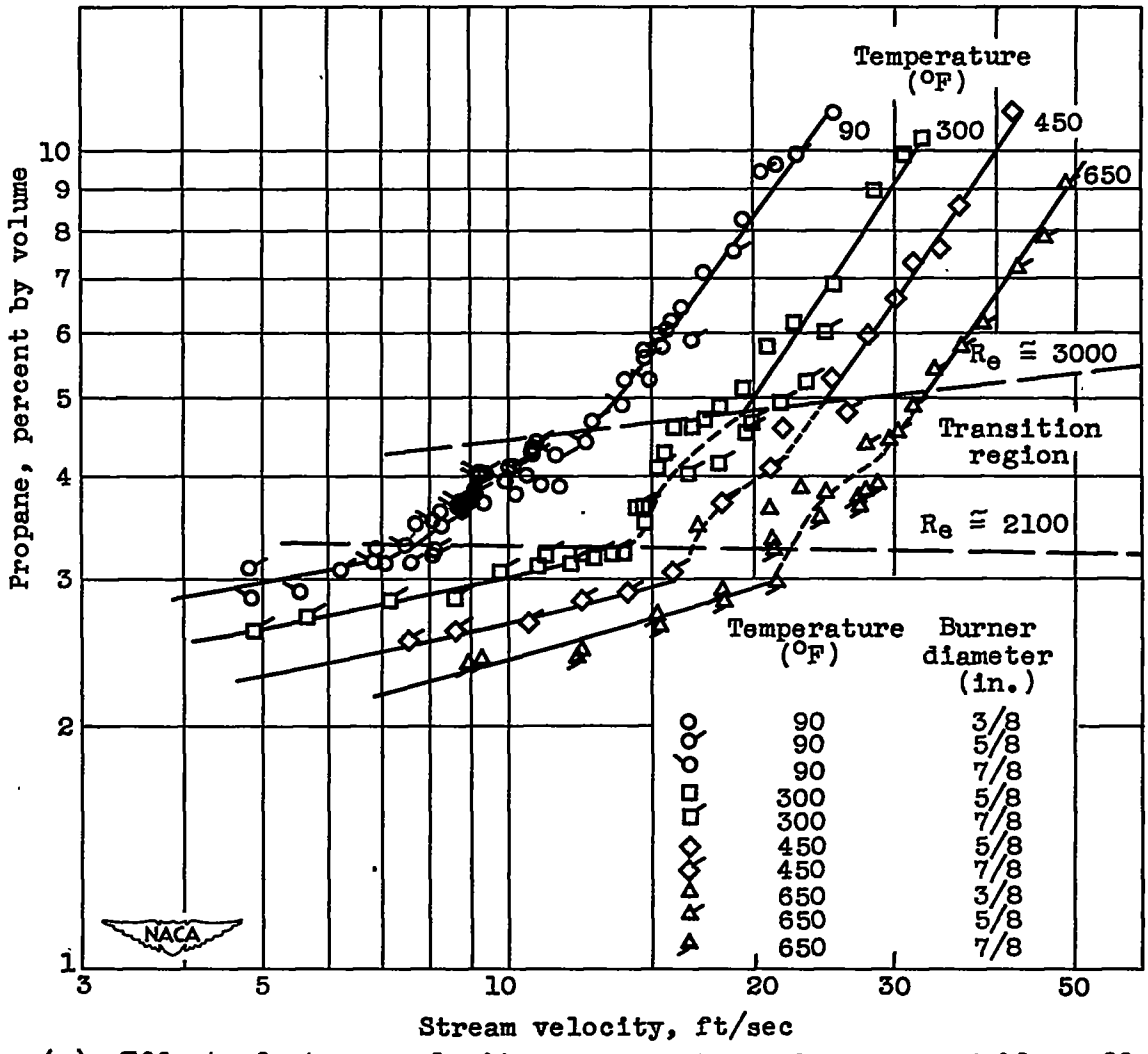
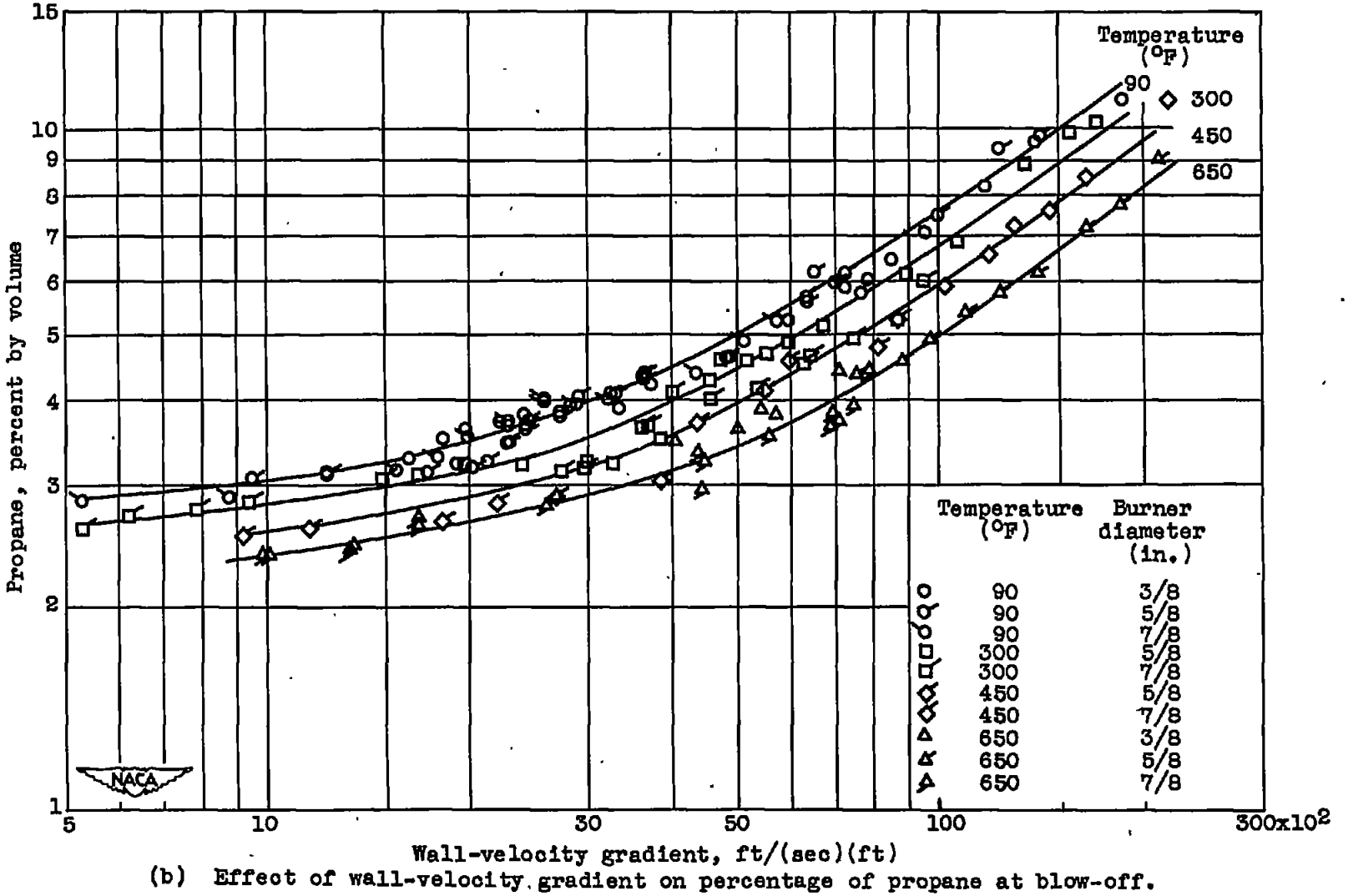


Figure 3. - Effect of temperature on speed of laminar propane-air flames.



(a) Effect of stream velocity on percentage of propane at blow-off.

Figure 4. - Blow-off of propane-air flames at various temperatures.



(b) Effect of wall-velocity gradient on percentage of propane at blow-off.

Figure 4. - Concluded. Blow-off of propane-air flames at various temperatures.

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