NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3765

SOME EFFECTS OF SMALL-SCALE FLOW DISTURBANCE ON NOZZLE-BURNER FLAMES

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SUMMARY

Small-diameter-wire grids were used as turbulence generators in a 1/2-inch nozzle burner to produce laminar-like propane-air flames subject to flow disturbances of a small scale compared to the reaction-zone thickness.

Both laminar-like and brush-like flames were obtained. Some laminar-like flames were obtained (for grid-disturbed flow) which had a slightly higher burning velocity than "true" laminar flames (no grid used). This finding agrees with Damkohler's theory on the effects of small-scale turbulence.

The brush-like flames were similar to those obtained with pipe turbulent flow. Thus, their burning-velocity dependence on a "flow disturbance" Reynolds number compared favorably with that obtained for pipe turbulent flames.

Hot-wire-anemometer measurements of flow disturbance intensity were made in the cold flow with and without the grids in place. The mean flow velocity range was from 100 to 1400 centimeters per second; equivalence ratios ranged from 0.99 to 1.32, depending upon the mean flow velocity.

INTRODUCTION

One of the purposes of turbulent-combustion research is to provide a better understanding of the mechanism governing the combustion performance of jet engines. One approach to this problem is to study the effect of turbulence on the combustion wave. In the past most investigations have been concerned with turbulence where the scale is large compared to the reaction-zone thickness. In this report the effects associated with small-scale turbulence (scale $\leq$ reaction-zone thickness) are investigated.

Damkohler (ref. 1) has considered the effects of small-scale turbulence on the combustion wave. In the presence of small-scale turbulence, the combustion wave, according to his theory, remains undistorted, but the transport processes are increased as a result of eddy diffusion. If this is true, the small-scale turbulent and the laminar flames are similar in appearance for a given fuel mixture and mean flow velocity and yet have different burning velocities, the turbulent flame having the higher burning velocity. The magnitude of this increase may be predicted by the following equation (ref. 1):

$$\frac{U_T}{U_L} = \sqrt{1 + \frac{\varepsilon}{\alpha}} \qquad (1)$$

This report observes this predicted effect. Small-diameter-wire grids were used to produce small-scale flow disturbances in the flow through a 1/2-inch nozzle burner. The intensities of flow disturbance u'/U were measured in the cold flow by constant-temperature hot-wire-anemometer equipment. The scale of the flow disturbance was not measured. Both laminar-like and brush-like flames were produced using the grids as flow disturbance generators. The burning velocities of the laminar-like flames could be measured as reliably as those of ordinary laminar flames, and the changes in burning velocity are compared with that predicted by Damkohler's theory. The physical appearance and burning-velocity dependence upon Reynolds number for the brush-like flames are compared with those for pipe turbulent flames.

SYMBOLS

A	fraction of open area of grid
d_p	pipe or nozzle-burner port diameter
d_w	wire diameter of grid
$\mathscr{L}_{Eu}$	Eulerian scale of turbulence or flow disturbance
$\mathscr{L}_{La}$	Lagrangian scale of turbulence or flow disturbance
$\mathscr{R}_{La}$	Lagrangian correlation coefficient
Re	Reynolds number, Ud_p/ν
Re_{grid}	grid Reynolds number, $Ud_w/\nu \times 1/A$

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Re'	turbulence or flow disturbance Reynolds number, $u'\mathcal{L}_{Eu}/\nu$
$\mathcal{T}_{re}$	reaction-zone thickness
t	time
t_{La}	characteristic time of turbulence or flow disturbance, $\mathcal{L}_{La}/u'$
U	mean flow velocity
U_L	laminar burning velocity
U_L'	grid-disturbed laminar burning velocity
U_T	flow-disturbed or turbulence burning velocity
u'	rms longitudinal velocity fluctuation
u'/U	intensity of turbulence or flow disturbance
x	distance downstream of grid
α	thermal diffusivity
ε	eddy diffusivity
ν	kinematic viscosity
τ	characteristic time of combustion, $\mathcal{T}_{re}/U_T$
φ	equivalence ratio

APPARATUS AND PROCEDURE

Four small-diameter-wire grids were selected on the basis of Dryden's equations (ref. 2), which describe the turbulence scale and intensity behind a grid placed in an airstream. Descriptions of the grids and their expected turbulence scales and intensities are listed in table I. The grids were placed 3/4 inch upstream of the port in the straight section of a 1/2-inch nozzle burner (see fig. 1). This 3/4-inch length represented a distance of at least 80 wire diameters behind each grid, which, according to reference 2, is necessary to obtain isotropic turbulence.

The 1/2-inch nozzle burner had a converging section with a contraction ratio of 64 and an annulus pilot and was water cooled (fig. 1). The top 3/4-inch straight section, containing the pilot and the water jacket, was made detachable so that the various grids could be placed in position to generate different levels of flow disturbance. The calming section was packed with numerous 1/16-inch I.D. stainless-steel tubes about 5 inches long to straighten the flow.

The combustible mixture was propane and air at room pressure and temperature. The mean velocity at the port was varied from 100 to 1400 cm/sec covering a range of nozzle Reynolds numbers, based on the port diameter, of 825 to 11,600. The equivalence ratio φ was varied from 0.99 to 1.32, depending upon the flow velocity. At velocities above 500 cm/sec, near stoichiometric flames often blew off in spite of the annular pilot, and it was necessary to use richer mixtures ($\varphi = 1.20$ to 1.32).

RESULTS AND DISCUSSION

Characteristics of Cold Flow Disturbances

Constant-temperature hot-wire-anemometer equipment was used to measure flow disturbance intensities u'/U generated in the cold flow by the various grids. The probe was a 0.04- by 0.0002-inch tungsten wire placed at the burner axis 1/16 inch above the port. The data from the measurements are listed in table II. Figure 2 shows the measured flow disturbance intensities (uncorrected for wire length) plotted against the mean flow velocity for the four small-scale turbulence grids, a 0.0177-inch-diameter-wire grid, and no grid. The 0.0177-inch-wire grid was not expected to produce a small scale compared to the reaction-zone thickness; it was used in the part of the work dealing with turbulent burning-velocity measurements for brush-like flames in order to obtain data at higher velocity fluctuations. The 0.0177-inch grid has a nominal mesh size of 16 and a 50-percent open area.

In general, the measured peak u'/U values for the four smaller grids were about 40 percent lower than those predicted by the intensity equation (ref. 2). This discrepancy is not surprising since the experimental conditions were different; other investigators (refs. 1 and 3) have found similar disagreement between measured and predicted values based on the intensity equation.

As a result of the work of reference 4, it is believed that the four smaller grids may have produced flow disturbances in the transition region. The wake development behind circular cylinders is studied in reference 4, and it is shown that there are three characteristic cylinder Reynolds number ranges for vortex shedding. These ranges are:

Vortex-shedding range	Reynolds number
Stable range, regular vortex streets formed, no turbulence	$40 < Re < 150$
Transition range	$150 < Re < 300$
Irregular range, periodic formation of vortices accompanied with turbulent velocity fluctuations	$300 < Re < 10{,}000$

Calculation of a grid Reynolds number $\frac{Ud_w}{\nu} \times \frac{1}{A}$ (ref. 5) for each of the four smaller grids showed that near the peak u'/U value for each of the grids, the grid Reynolds number was about 140, which corresponds quite closely to the beginning of the transition range for circular cylinders. Table II lists the grid Reynolds numbers for the various grids at several velocities. The range of Reynolds numbers for each grid was small, and even for the largest of the four smaller grids, the 0.0090-inch-wire grid, the grid Reynolds numbers ranged only from 21 to 296. Thus, it may well be that the flow disturbances produced by these small grids were in the stable and transition ranges of vortex shedding. The calculation of grid Reynolds number for only the 0.0177-inch grid showed that the flow disturbances were well into the irregular range, since the grid Reynolds numbers ranged from 63 to 780. Consequently, the more appropriate term "flow disturbance" rather than turbulence was used to describe the grid-disturbed flow.

Some u'/U measurements were also made at the burner axis with the probe 7/16 and $1\frac{5}{8}$ inches above the port. These measurements are compared in table III with those made with the probe 1/16 inch above the port. At 7/16 inch above the port the u'/U values were 5 to 10 percent lower, and at $1\frac{5}{8}$ inch above the port the u'/U values were $1\frac{1}{2}$ to 3 times higher. The lower u'/U value at the 7/16-inch position indicated that the probe was probably in a region where normal decay of flow disturbance was occuring behind a grid; the higher u'/U value at the $1\frac{5}{8}$-inch position indicated that the probe was in a region where the flow disturbance level was increased by contributions from the free-jet mixing region.

The laminar velocity range of 110 to 600 cm/sec for the nozzle burner with no grid was that range over which laminar-like flames could be observed. However, for this velocity range residual velocity fluctuation values ranging from 1.2 to 2.8 cm/sec were observed, which suggests that, for this type experimental apparatus, the observed "laminar" velocity might be slightly dependent on flow rate.

Since no scale measurements were made, the appropriate equation (ref. 2) was used to calculate the flow disturbance scale produced by the smaller grids. For a distance downstream of the grid of 3/4 inch, the scale values were about 0.0125 centimeter for all four grids.

Appearance of Flames Subject to Small-Scale Flow Disturbance

Two distinct types of flames were observed when the four smaller grids were used to produce flow disturbances in the cold flow.

Laminar-like flame. - The first type was laminar-like in appearance and was found in the velocity range of 150 to 600 cm/sec when the 0.0055-inch-wire grid was used. Very low intensity flow disturbances were produced in this region. Figure 3 shows a grid disturbed and an undisturbed propane-air flame for an equivalence ratio φ of 1.00 and a mean flow velocity U of 328 cm/sec with and without a 0.0055-inch-wire grid in place.

A total-area method, based on the luminous cone, was used to compare burning velocities, and the results are shown in table IV. The burning velocities observed for laminar-like flames were about 5 percent higher than those for "true" laminar flames (no grid used). This 5-percent increase, although small, may be significant since the burning-velocity increase predicted by equation (1)

$$U_T/U_L = U_L'/U_L = \sqrt{1 + \frac{\varepsilon}{\alpha}}$$

is also very small.

A predicted burning-velocity increase was calculated using the preceding equation, where the eddy diffusivity ε was determined from Taylor's theory of diffusion (ref. 6):

$$\varepsilon = u'^2 \int_0^{\tau} \mathscr{R}_{La}\, dt$$

The upper limit of integration τ was the characteristic time of combustion:

$$\tau = \mathscr{T}_{re}/U_T$$

with τ evaluated by assuming that the reaction-zone thickness $\mathscr{T}_{re}$ was 0.05 centimeter and the turbulence burning velocity U_T was 1.05 U_L

($U_L = 35$ cm/sec). The Lagrangian correlation coefficient $\mathcal{R}_{La}$ was assumed to have the observed form (ref. 2):

$$\mathcal{R}_{La} = e^{-t/t_{La}}$$

where the characteristic time of the turbulence t_{La} is defined as

$$t_{La} = \mathcal{L}_{La}/u'$$

For $u'/U = 0.7$ percent and $U = 400$ cm/sec (see fig. 2), it follows from reference 7 that

$$\mathcal{L}_{La} = 3.3\,\mathcal{L}_{Eu}$$

The above analysis resulted in a predicted burning-velocity increase of about 3 percent, which compared well with the observed increase of about 5 percent.

Brush-like flame. - The second type of flame was slightly wrinkled or brush-like in appearance, depending upon the magnitude of the flow disturbance produced. These flames were found in the velocity range of 600 to 1200 cm/sec, a range in which the flow disturbance intensity was appreciable. With the 0.0055-, 0.0075-, and 0.0090-inch grids at velocities greater than 700 cm/sec, the flames appeared similar to pipe turbulent flames observed by other investigators. Figure 4 shows some of these flow-disturbed, rich propane-air flames at a velocity of 1013 cm/sec using these three grids.

In a further attempt to obtain laminar-like flames subject to small-scale flow disturbances at velocities above 600 cm/sec, a mixture of 3 percent propane, 17 percent oxygen, and 80 percent nitrogen (ref. 8) was used to obtain flames with thicker reaction zones. Reference 9 indicates that the reaction-zone thickness for such a flame varies inversely with the product of the density of the unburnt gas, the flame speed, and the mean molal specific heat. For the preceding mixture the density and the mean molal specific heat are approximately the same as those for a near stoichiometric propane-air mixture, but the flame speed ratio is about 1/2. Thus, for this mixture the reaction-zone thickness was approximately doubled. However, the flames obtained were also wrinkled or brush-like in appearance.

Turbulent Burning Velocities for Some Flow-Disturbed Flames

Turbulent burning velocities for the brush-like flames were calculated on the same basis as used in reference 10. The burning velocity was taken as equal to the volume flow divided by a mean flame area, which was based on a line faired through the center of the visible flame brush. The three larger grids (wire diam., 0.0177, 0.0090, and 0.0075 in.) were used to produce these rich, flow-disturbed propane-air flames ($\varphi = 1.01$ to 1.32).

The results of the turbulent burning-velocity measurements are listed in table V and summarized in figure 5. The data are plotted in a manner similar to that used in reference 10, in which the correlating parameters were $U_T/U_L d_p^{0.26}$ and Reynolds number Re. For comparison, the data of reference 9 and of the present investigation are plotted in terms of $U_T/U_L \mathscr{L}_{Eu}^{0.26}$ and $Re' = \frac{u' \mathscr{L}_{Eu}}{\nu}$, a Reynolds number of the flow disturbance (fig. 5). Such a plot may be used since, for the case of fully developed pipe turbulence, the following relations hold (ref. 10):

$$\mathscr{L}_{Eu} = k_1 \times d_p$$

$$u' = k_2 \times U$$

For the data of reference 10, the term $U_T/U_L \mathscr{L}_{Eu}^{0.26}$ was calculated assuming that $\mathscr{L}_{Eu} = 0.08\ d_p$ (ref. 11). Since data for the 5/8-inch-diameter burner were used, $\mathscr{L}_{Eu}$ equals 0.127 centimeter. Re' was calculated, assuming that $u' = 0.03\ U$ (ref. 12). A least squares line through these calculated values may be expressed by

$$\frac{U_T}{U_L \mathscr{L}_{Eu}^{0.26}} = 1.23\ (Re')^{0.222}$$

For the present data, $U_T/U_L \mathscr{L}_{Eu}^{0.26}$ was obtained assuming $\mathscr{L}_{Eu}$ could be calculated from the appropriate equation (ref. 2). The calculated $\mathscr{L}_{Eu}$ values from the 0.0090- and 0.0075-inch-diameter-wire grids are listed in table I. For the 0.0177-inch-diameter-wire grid, $\mathscr{L}_{Eu}$ was estimated to be about 0.0125 centimeter. (The scale equation of ref. 2 is not applicable when $x < 80$ wire diam.) Re' for the three grids was calculated using measured values of u' and $\mathscr{L}_{Eu} = 0.0125$ centimeter. A least squares line through these data may be represented by the equation

$$\frac{U_T}{U_L \mathscr{L}_{Eu}^{0.26}} = 3.61\ (Re')^{0.286}$$

For purposes of comparing the two sets of data, the correlating curve for the data of reference 10 may be normalized. This normalized curve (dashed line of fig. 5) has its slope preserved and intersects the lowest Re' value obtained herein from brush-like flames. Thus, for the range of Re' investigated, both sets of data, one for pipe turbulent and the other for grid-disturbed flames, show approximately the same relation between turbulent burning velocity and Re'.

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CONCLUSIONS

The disturbed laminar-like flames had burning velocities about 5 percent higher than those observed for the undisturbed laminar flames, which agrees with Damkohler's predictions. For small-scale flow disturbances of significantly higher intensities, brush-like flames were observed. These flames were similar to pipe turbulent flames with regard to their physical appearance and burning-velocity dependence on the flow disturbance Reynolds number.

Obtaining laminar-like flames with flows in which flow disturbance intensities were high would have been desirable. However, velocities above 600 centimeters per second invariably result in brush-like flames. This inability to obtain laminar-like flames at high flow disturbance intensities may be associated with several possible factors:

(1) Although the grids may be generating small-scale flow disturbances near the port, the scale does not necessarily remain small relative to the reaction-zone thickness at some distance above the port.

(2) If, as indicated in reference 13, the effect of approach stream turbulence scale on flame-front distortion is unimportant, then the brush-like flames may result when a small disturbance produced by a grid is amplified by the flame itself as described in a discussion by G. H. Markstein (ref. 14).

(3) Since a portion of the flame was probably in the intense mixing region above the port, the flame-front distortions may be due to a disturbance from the jet shearing action between the combustible gas and secondary air in this region.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 24, 1956

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TABLE I. - DESCRIPTION OF SMALL-WIRE GRIDS AND EXPECTED TURBULENCE SCALES AND INTENSITIES

Wire diameter of grid, in.	Mesh	Open area, percent	Expected turbulence[a]	
			Scale, $\mathscr{L}_{Eu}$, mm	Intensity, u'/U, percent
0.0035	90	49	0.12	2.00
.0055	42	59	.13	2.75
.0075	26	65	.13	3.75
.0090	20	67	.12	4.30

[a] Scale and intensity calculated by the following equations (ref. 2) for $x = 3/4$ in.:

$$\left(\frac{\mathscr{L}_{Eu}}{d_w}\right)^2 = 0.264\left[1 + 0.04\left(\frac{x}{d_w} - 80\right)\right]$$

$$\left(\frac{U}{u'}\right)^2 = 400\left[1 + 0.04\left(\frac{x}{d_w} - 80\right)\right]$$

TABLE II. - MEASURED FLOW DISTURBANCE INTENSITIES AND GRID REYNOLDS NUMBERS AT VARIOUS MEAN FLOW VELOCITIES

Mean flow velocity, U, cm/sec	Wire diameter of grid, in.										
	No grid	0.0035		0.0055		0.0075		0.0090		0.0177	
	Flow disturbance intensity, u'/U, percent	Flow disturbance intensity, u'/U, percent	Re_{grid}	Flow disturbance intensity, u'/U, percent	Re_{grid}	Flow disturbance intensity, u'/U, percent	Re_{grid}	Flow disturbance intensity, u'/U, percent	Re_{grid}	Flow disturbance intensity, u'/U, percent	Re_{grid}
107	1.02	1.05	13	1.12	16	1.10	20	1.10	21	1.12	63
212	.80	.82	25	.86	33	.80	46	.76	45	.72	124
316	.66	.72	37	.74	49	.74	61	.64	67	3.14	184
384	.60	.65	45	.68	59	.58	74	.62	81	3.24	224
452	.56	----	53	.80	69	.82	86	.81	100	4.80	265
705	.48	.80	83	.68	108	1.84	134	2.96	156	4.16	413
957	.42	.72	113	1.42	147	1.76	182	2.84	212	3.60	560
1210	.40	.86	142	1.50	186	1.54	230	2.70	268	3.32	708
1334	----	.94	157	1.44	205	----	---	2.60	296	3.26	780

TABLE III. - VARIATION OF MEASURED FLOW DISTURBANCE INTENSITIES WITH HEIGHT ABOVE BURNER PORT

Wire diameter of grid, in.	Mean flow velocity, U, cm/sec	Ratio of flow disturbance intensity, u'/U	
		Height above burner, in.	
		$\frac{7}{16}$ (a)	$1\frac{5}{8}$ (b)
0.0090	710	0.87	1.6
	1332	.90	1.84
0.0075	710	0.94	3.3
	1332	.95	2.6
0.0055	711	1.00	3.8
	1332	.92	---

[a] Ratio of u'/U values at 7/16 in. over u'/U values at 1/16 in. above port.

[b] Ratio of u'/U values at $1\frac{5}{8}$ in. over u'/U values at 1/16 in. above port.

TABLE IV. - BURNING-VELOCITY COMPARISONS BETWEEN GRID-DISTURBED AND UNDISTURBED PROPANE-AIR FLAMES

Mean flow velocity, U, cm/sec	Equivalence ratio, φ	Flame area, a_1, sq cm	Flame area, a_2, sq cm	Burning-velocity ratio, $\frac{U'_L}{U_L} = \frac{a_2}{a_1}$
		Grid[a]	No grid[b]	
164	0.99	4.95	5.13	1.06
328	1.00	9.13	9.19	1.05
493	1.00	12.13	12.62	1.04

[a] Laminar-like flames.

[b] True laminar flames.

TABLE V. - TURBULENT BURNING-VELOCITY MEASUREMENTS FOR SOME GRID-INDUCED TURBULENT PROPANE-AIR FLAMES

Mean flow velocity, U, cm/sec	Volume flow, cc/sec	Equivalence ratio, φ	Wire diameter of grid, in.	Flame area, sq cm	Turbulent burning velocity, U_T, cm/sec	Laminar burning velocity, U_L, cm/sec	U_T/U_L	$\mathscr{L}_{Eu}^{0.26}$ (a)	$\frac{U_T}{U_2 \mathscr{L}_{Eu}^{0.26}}$, cm^{-1}	Rms longitudinal velocity fluctuation, u', cm/sec (b)	$Re' = \frac{u' \mathscr{L}_{Eu}}{\nu}$
500	632	1.31	0.0177	13.62	46.4	33.2	1.37	0.320	4.28	2.45	1.99
494	625	1.01	↓	11.90	52.5	36.0	1.46	↓	4.57	↓	↓
496	627	1.08	↓	12.03	52.1	37.3	1.40	↓	4.38	↓	↓
497	629	1.14	↓	12.22	51.5	39.2	1.31	↓	4.09	↓	↓
498	631	1.20	↓	12.40	50.8	38.6	1.32	↓	4.13	↓	↓
794	992	1.30	.0075	24.21	40.9	33.8	1.21	↓	3.80	14.3	1.16
794	992	↓	.0090	21.02	47.2	↓	1.40	↓	4.37	23.3	1.89
794	992	↓	.0177	20.30	48.8	↓	1.44	↓	4.52	31.4	2.55
1060	1340	1.31	.0075	30.10	44.6	33.2	1.34	↓	4.19	17.8	1.45
1060	1340	1.31	.0090	26.80	50.0	33.2	1.51	↓	4.71	29.7	2.42
1060	1340	1.31	.0177	25.00	53.7	33.2	1.62	↓	5.06	36.9	3.00
853	1078	1.28	.0075	25.70	42.0	35.1	1.19	↓	3.72	15.4	1.25
853	↓	↓	.0090	25.00	43.2	↓	1.24	↓	3.87	24.6	2.00
853	↓	↓	.0177	19.83	54.4	↓	1.55	↓	4.85	32.0	2.60
1194	1510	1.31	.0090	30.05	50.2	33.2	1.51	↓	4.73	32.5	2.64
1194	1510	1.31	.0177	26.80	56.4	33.2	1.70	↓	5.32	39.7	3.23
1190	1506	1.32	.0075	32.90	45.7	32.2	1.42	↓	4.43	18.6	1.51
1330	1680	1.24	.0075	32.40	51.9	36.2	1.43	↓	4.48	20.8	1.69

[a] Calculated with equation of ref. 2 for x = 3/4 in.; $\mathscr{L}_{Eu}$ for 0.0177-in. grid estimated to be 0.0125 cm.

[b] From fig. 2.

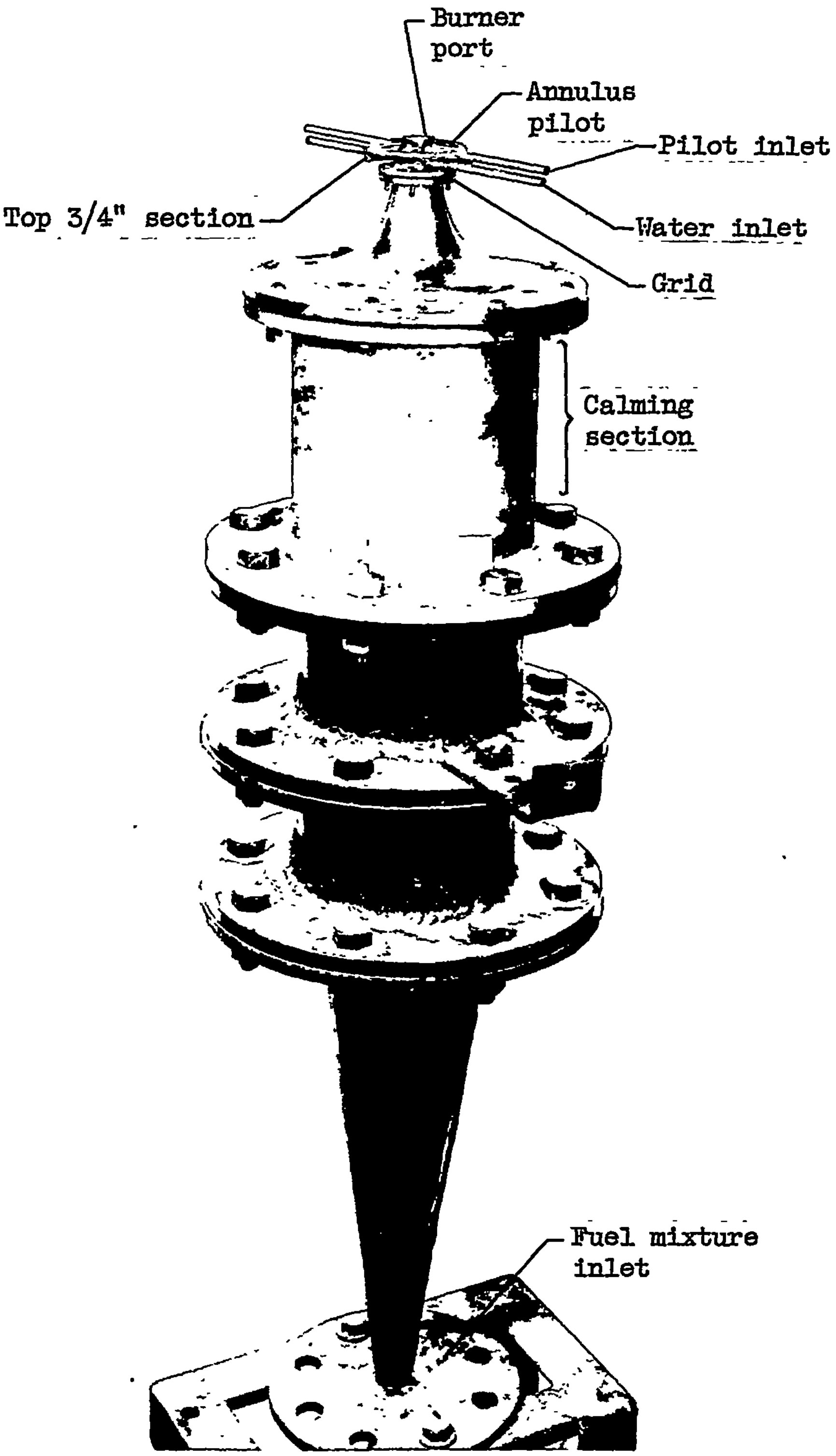

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Figure 1. - 1/2-Inch nozzle burner.

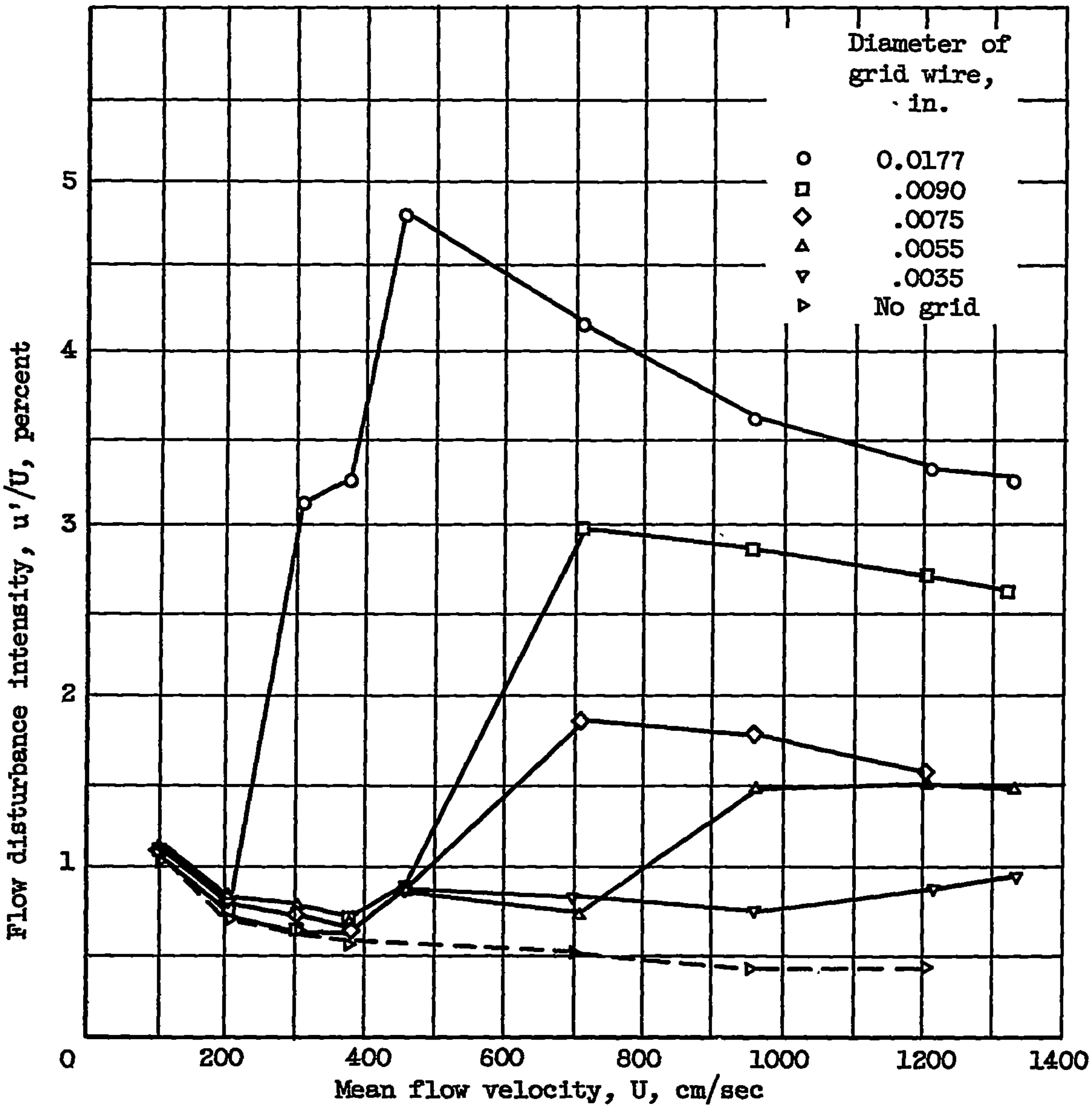
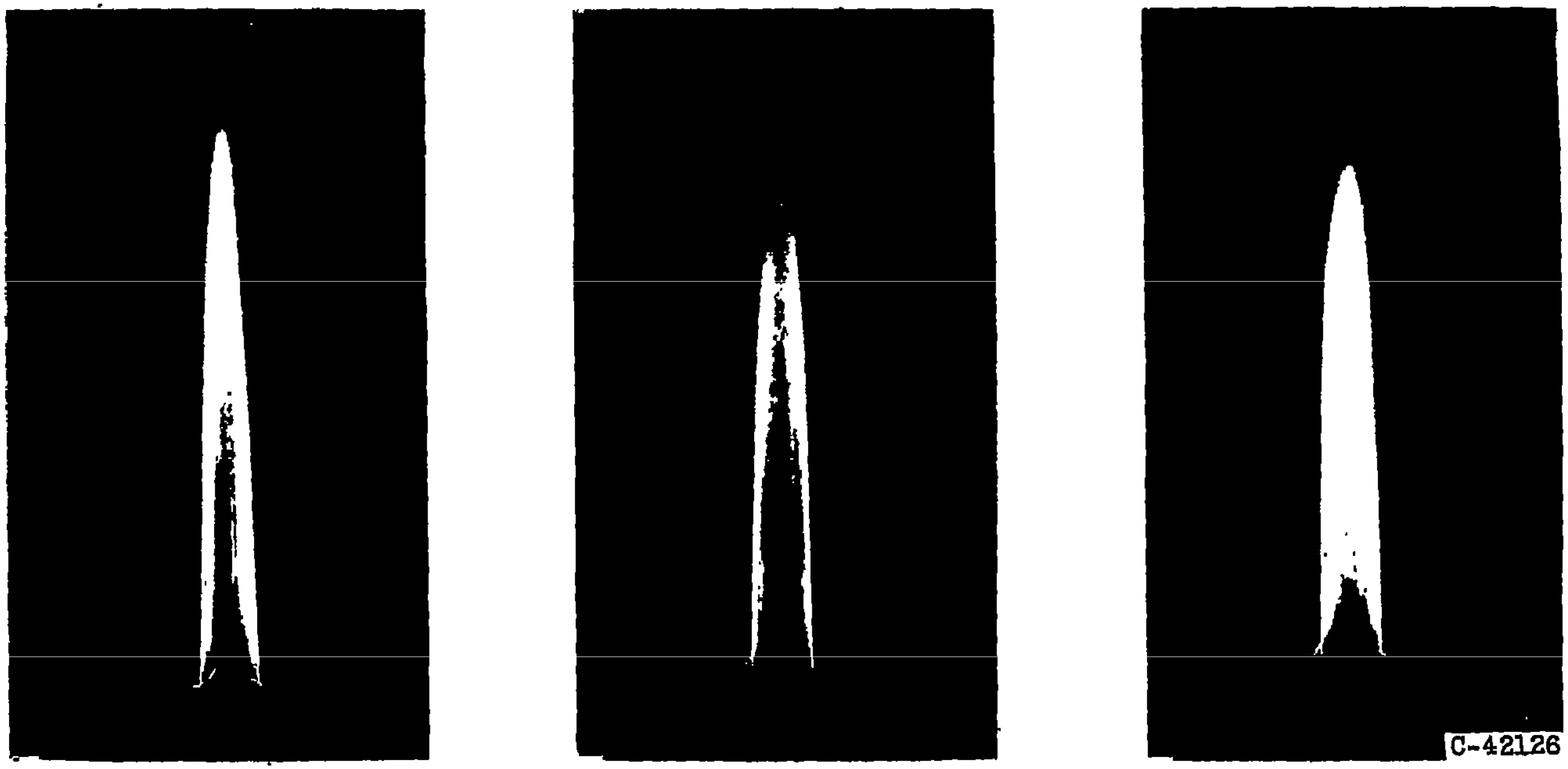


Figure 2. - Variation of flow disturbance intensities with mean velocities for various grids.

No grid

0.0055-Inch-diameter-wire grid

Figure 3. - Disturbed and undisturbed laminar propane-air flames. Equivalence ratio, 1.00; mean flow velocity, 328 cm/sec.



0.0055-Inch-wire grid;
rms longitudinal velocity
fluctuation, 14.7 cm/sec

0.0075-Inch-wire grid;
rms longitudinal velocity
fluctuation, 17.2 cm/sec

0.0090-Inch-wire grid;
rms longitudinal velocity
fluctuation, 28.4 cm/sec

Figure 4. - Grid-induced turbulent propane-air flames. Equivalence ratio, 1.31; mean flow velocity, 1013 cm/sec.

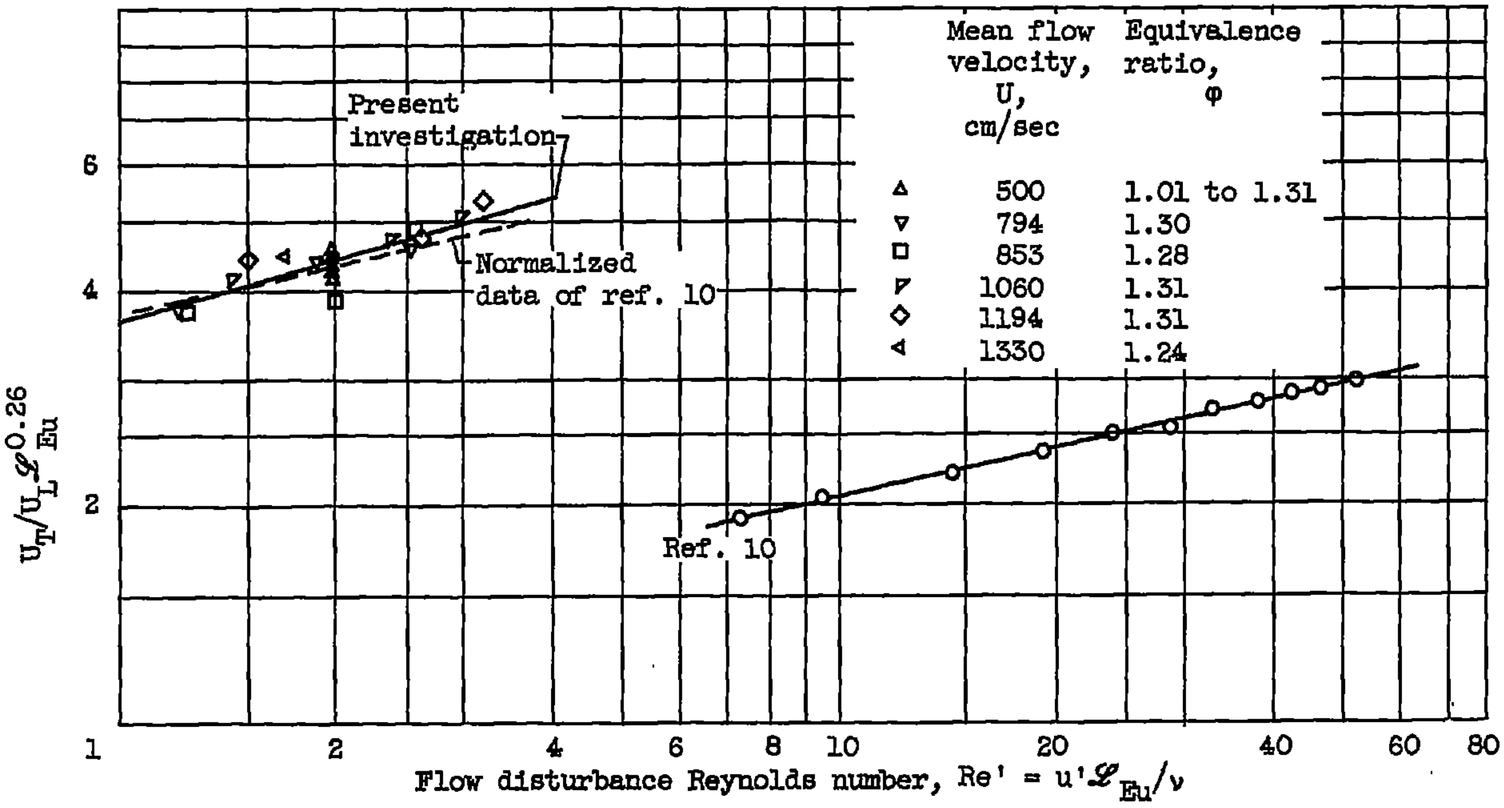


Figure 5. - Comparison of turbulent burning-velocity measurements of reference 10 with those from present investigation.

NACA - Langley Field, Va.