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► **To cite this version:**

Andrei N. Lipatnikov, Vladimir Sabelnikov, Shinnosuke Nishiki, Tatsuya Hasegawa. Does flame-generated vorticity increase turbulent burning velocity?. *Physics of Fluids*, 2018, 30, pp.081702. 10.1063/1.5046137. hal-02068663

HAL Id: hal-02068663

<https://hal.science/hal-02068663v1>

Submitted on 15 Mar 2019

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Does Flame-Generated Vorticity Increase Turbulent Burning Velocity?

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(Dated: 19 June 2018)

Direct Numerical Simulation data obtained from a statistically stationary, 1D, planar, weakly turbulent, premixed flame, which is associated with the flamelet combustion regime, are analyzed in order to show that generation of vorticity due to baroclinic torque within flamelets can impede wrinkling the reaction surface, reduce its area, and decrease burning rate. These data call for revisiting the widely-accepted concept of combustion acceleration due to flame-generated turbulence.

PACS numbers: 47.70.Fw, 82.33.Vx, 47.27.-i

Keywords: premixed turbulent burning, flame-generated turbulence, thermal expansion, combustion acceleration, DNS

The problem of the influence of combustion-induced thermal expansion on turbulent flow within a premixed flame brush has been challenging the combustion community for decades. The problem was posed by Karlovitz et al.¹ and by Scurlock and Grover² who introduced a concept of flame-generated turbulence in order to explain unexpectedly high burning rates obtained in some early experiments. Since that pioneering work, the thermal expansion effects were in the focus of research into turbulent combustion, but progress in modeling them has yet been rather moderate, as reviewed elsewhere.³⁻⁵ Nevertheless, the concept^{1,2} of combustion acceleration due to flame-generated turbulence has never been disputed, to the best of the present authors' knowledge, at least in the case of weak or moderate turbulence associated with a well-pronounced increase⁶ in burning rate by the rms turbulent velocity u' . The present letter aims at putting this widely-accepted concept into question by showing that flame-generated vorticity can smooth wrinkles of the local flame surface, thus, reducing its area and, consequently, decreasing turbulent burning velocity U_t .

For this purpose, Direct Numerical Simulation (DNS) data^{7,8} will be analyzed. Since the data were comprehensively discussed by various research groups,⁷⁻²³ we will restrict ourselves to a brief summary of those compressible simulations. They dealt with statistically planar, 1D, adiabatic flames modeled by unsteady 3D continuity, Navier-Stokes, and energy equations, as well as the ideal gas state equation. Combustion chemistry was reduced to a single reaction. The Lewis and Prandtl numbers were equal to 1.0 and 0.7, respectively. The mixture state was characterized with a single combustion progress variable $c = (T - T_u)/(T_b - T_u)$. Temperature-dependence of molecular transport coefficients was taken into account, e.g., the kinematic viscosity $\nu = \nu_u(T/T_u)^{0.7}$. Here, T is the temperature, subscripts u and b designate unburned reactants and burned products, respectively.

The computational domain was a rectangular box $\Lambda_x \times \Lambda_y \times \Lambda_z$, where $\Lambda_x = 8$ mm and $\Lambda_y = \Lambda_z = 4$ mm. It was resolved using a uniform rectangular ($2\Delta x = \Delta y = \Delta z$) mesh of $512 \times 128 \times 128$ points. The flow was periodic in y and z directions.

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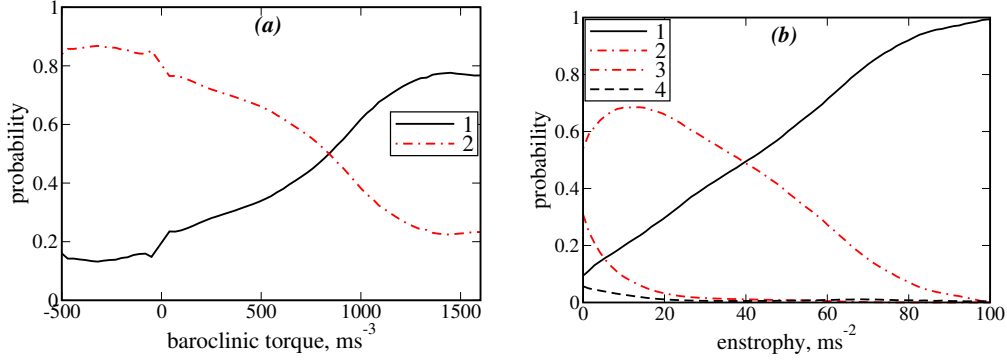


FIG. 1. Probabilities of negative (curves 1 and 4) and positive (curves 2 and 3) stretch rates conditioned on the local value of (a) baroclinic torque term $\omega \cdot (\nabla \rho \times \nabla p) / \rho^2$ in the transport equation for the enstrophy $\Omega = \omega \cdot \omega$ and (b) enstrophy. In sub-figure (b), curves 1-2 and 3-4 are associated with the positive and negative, respectively, baroclinic torque term.

50 As discussed elsewhere,⁷ homogeneous isotropic turbulence ($u' = 0.53$ m/s, an integral
 51 length scale $L = 3.45$ mm, and the turbulent Reynolds number $Re_t = u'L/\nu_u = 96$) was
 52 generated in a separate box and was injected into the computational domain through its left
 53 boundary $x = 0$. At $t = 0$, a planar laminar flame was embedded into statistically the same
 54 turbulence assigned for the velocity field in the entire computational domain. Subsequently,
 55 the mean inflow velocity U was increased twice, at $t = t_1$ and $t = t_2$, in order to keep the
 56 flame in the computational domain till the end t_3 of the simulations.

57 Three cases characterized by different density ratios $\sigma = \rho_u / \rho_b$ were studied. In the
 58 present letter, we will restrict ourselves to results obtained in a single case H, character-
 59 ized by the largest $\sigma = 7.53$, because significant amount of flame-generated vorticity was
 60 documented in this case.¹⁵ As shown elsewhere,¹⁶ premixed turbulent flame H (the laminar
 61 flame speed $S_L = 0.6$ m/s and thickness $\delta_L = (T_b - T_u) / \max\{|\nabla T|\} = 0.217$ mm) is well
 62 associated with the flamelet combustion regime.^{24,25}

63 Figure 1 shows that the probability of negative (curves 1 and 4) stretch rates²⁶ $\dot{s} =$
 64 $\nabla \cdot \mathbf{u} - \mathbf{nn} : \mathbf{u} + S_d \nabla \mathbf{n}$ is higher than the probability of $\dot{s} > 0$ (curves 2 and 3) in regions
 65 characterized by a large magnitude of the local enstrophy $\Omega = \omega \cdot \omega$ or the local baroclinic
 66 torque term $T_{bt} = \omega \cdot (\nabla \rho \times \nabla p) / \rho^2$ in the transport equation¹⁵ for the enstrophy. Note that
 67 the relation between the two probabilities is opposite if the entire flame brush is considered.
 68 Here, \mathbf{u} is the velocity vector, $\mathbf{n} = -\nabla c / |\nabla c|$ is the unit vector locally normal to an
 69 iso-scalar surface of $c(\mathbf{x}, t) = \text{const}$, $\omega = \nabla \times \mathbf{u}$ is the vorticity vector, p is the pressure,
 70 $S_d = [\nabla \cdot (\rho D \nabla c) + W] / (\rho |\nabla c|)$ is the local displacement speed, D is the molecular diffusivity
 71 of c , and W is the mass rate of product creation.

72 Since the rate $A_F^{-1} dA_F / dt$ of an increase or decrease in the logarithm of an infinitesimal
 73 area A_F of a propagating surface is equal to the local stretch rate,²⁶ Fig. 1 indicates that
 74 the area of a surface of $c(\mathbf{x}, t) = \text{const}$ is statistically reduced in regions associated with the
 75 strongest generation of vorticity and enstrophy due to the baroclinic torque.

76 This trend is further supported in Fig. 2, which shows that (a) relative (in volumes
 77 characterized by $T_1 < T_{bt} < T_2$ when compared to the entire flame brush) mean bulk rate

$$\langle \delta A_F | c_1 < c < c_2, T_1 < T_{bt} < T_2 \rangle = \frac{\int_{t_2}^{t_3} \iiint \dot{s} |\nabla c| \Pi(c_1 < c < c_2) \Pi(T_1 < T_{bt} < T_2) d\mathbf{x} dt}{\int_{t_2}^{t_3} \iiint \dot{s} |\nabla c| \Pi(c_1 < c < c_2) d\mathbf{x} dt} \quad (1)$$

78 of an increase in flame surface area and (b) the mean local rate

$$\left\langle \frac{d\Sigma}{dt} \middle| c_1 < c < c_2, T_1 < T_{bt} < T_2 \right\rangle = \frac{\int_{t_2}^{t_3} \iiint \dot{s} |\nabla c| \Pi(c_1 < c < c_2) \Pi(T_1 < T_{bt} < T_2) d\mathbf{x} dt}{\int_{t_2}^{t_3} \iiint \Pi(c_1 < c < c_2) \Pi(T_1 < T_{bt} < T_2) d\mathbf{x} dt} \quad (2)$$

80

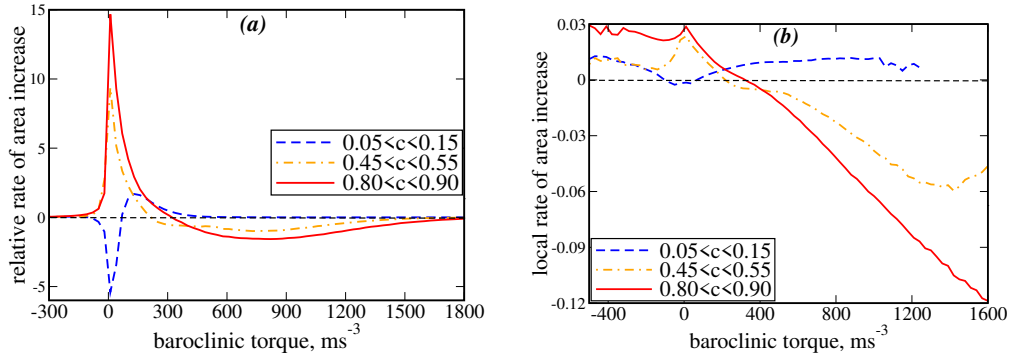


FIG. 2. (a) Relative bulk rate of an increase in flame surface area, given by Eq. (1), and (b) normalized local rate of an increase in flame surface area, given by Eq. (2), vs. baroclinic torque term $\boldsymbol{\omega} \cdot (\nabla \rho \times \nabla p) / \rho^2$ in the enstrophy transport equation. The rate is normalized using $(D_u / S_L^2)^3$.

81 of an increase in the area are negative in regions characterized by a high magnitude of the
 82 baroclinic torque term T_{bt} provided that the local value of $c(\mathbf{x}, t)$ is sufficiently large. Here,
 83 function $\Pi(q_1 < q < q_2) \equiv H(q - q_2) - H(q - q_1)$ is equal to unity if $q_1 < q < q_2$ and
 84 vanishes otherwise, $H(x)$ is Heaviside function, T_{bt} -step $T_2 - T_1 = 30 \text{ ms}^{-3}$, $\Sigma = |\nabla c|$ is
 85 flame surface density,²⁷ and the integral in the numerator of Eq. (1) or (2) characterizes
 86 the rate of an increase in flame surface area, because $dA_F/dt = \dot{s}A_F = \dot{s}|\nabla c|dV$.

87 The rates given by Eqs. (1) and (2) are predominantly positive in the vicinity of flamelet
 88 leading edge ($0.05 < c < 0.15$), but becomes negative in the middle ($0.45 < c < 0.55$)
 89 of flamelets and, especially, within flamelet's reaction zones ($0.80 < c < 0.90$) provided
 90 that the magnitude of T_{bt} is sufficiently large. Therefore, vorticity generation by baroclinic
 91 torque within flamelet's preheat zones impedes increasing the area of the reaction zones and
 92 burning velocity, contrary to the common concept of flame-generated turbulence.

93 The fact that flame-generated vorticity can impede wrinkling flame surface is well-known
 94 in the theory of the hydrodynamic instability of laminar premixed flames.²⁸ Within the
 95 framework of the theory, the incoming flow of unburned reactants is potential, but the rota-
 96 tional component of the velocity field is generated behind the flame and acts at smoothing
 97 flame-surface bulges, thus, reducing the destabilizing effect of the potential flow, e.g., see
 98 Eq. (40) in a recent review paper.⁴ Nevertheless, this classical theoretical result, which is
 99 qualitatively consistent with the present DNS data, has yet been beyond the mainstream
 100 discussion of the influence of flame-generated turbulence on burning rate.

101 Finally, it is worth stressing that the present letter does not claim that the influence of
 102 combustion-induced thermal expansion on turbulence reduces burning rate. The potential
 103 velocity perturbations can overwhelm the rotational perturbations and can result in increas-
 104 ing burning rate, as occurs in the case of a hydrodynamically unstable laminar premixed
 105 flame.²⁸ However, if turbulence is considered to be inherently rotational flow, the concept of
 106 combustion acceleration due to flame-generated turbulence should be revisited. In particu-
 107 lar, models developed for predicting an increase in burning rate by vorticity in the incoming
 108 turbulent flow are unlikely to be useful for describing a decrease in flamelet surface area
 109 and burning rate due to flame-generated vorticity. In other words, the influence of the
 110 incoming turbulence on burning rate should clearly be distinguished from the influence of
 111 flame-generated turbulence on the burning rate and the two effects can be opposite.

112 ANL gratefully acknowledges the financial support by the Chalmers Area of Advance
 113 Transport, and by the Combustion Engine Research Center (CERC). VAS gratefully ac-
 114 knowledges the financial support by ONERA and by the Grant of the Ministry of Education
 115 and Science of the Russian Federation (Contract No. 14.G39.31.0001 of 13.02.2017).

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