



## Conditioned structure functions in turbulent hydrogen/air flames

Downloaded from: <https://research.chalmers.se>, 2026-04-04 11:35 UTC

Citation for the original published paper (version of record):

Sabelnikov, V., Lipatnikov, A., Nikolay, N. et al (2022). Conditioned structure functions in turbulent hydrogen/air flames. *Physics of Fluids*, 34(8). <http://dx.doi.org/10.1063/5.0096509>

N.B. When citing this work, cite the original published paper.



32 **I. INTRODUCTION**

33 Substantial influence of combustion-induced thermal expansion on turbulence in flames has  
34 been known since the seminal papers by Karlovitz et al.<sup>1</sup> and Scurlock and Grover.<sup>2</sup> Over the  
35 past two decades, rapid development of Direct Numerical Simulation (DNS) methods and  
36 tools allowed researchers<sup>3-9</sup> to reveal various manifestations of this influence and to document  
37 significant changes of basic features of turbulence in premixed flames. Such results reviewed  
38 elsewhere<sup>10-13</sup> call for revisiting the problem of modeling turbulence in reacting flows.  
39 Although some DNS data indicate that certain combustion-induced thermal expansion effects  
40 are weakly pronounced in highly turbulent flames,<sup>14-21</sup> these data do not deny the need for  
41 advancing models of turbulence in flames. Indeed, firstly, there is no widely recognized  
42 criterion for assessing importance of the combustion-induced thermal expansion effects under  
43 specific conditions. Secondly, weak influence of the thermal expansion on certain turbulence  
44 characteristics does not prove that all other turbulence characteristics are also weakly affected  
45 by the thermal expansion under the same conditions. For instance, recent experimental  
46 data<sup>22,23</sup> obtained from highly turbulent lean methane-air swirl flames show importance of  
47 thermal expansion effects such as vorticity generation due to baroclinic torque<sup>22</sup> or back-  
48 scatter.<sup>23</sup>

49 Thus, there is a clear need for development of an advanced model of turbulence in flames,  
50 which could predict phenomena revealed recently and reviewed elsewhere.<sup>10-13</sup> However, no  
51 comprehensive modeling framework to represent distinct roles of thermal expansion on  
52 turbulence exists today. To develop such a framework, more knowledge about the influence  
53 of combustion-induced thermal expansion on turbulence is required first. For this reason, a  
54 set of methods applied to explore this influence was greatly extended recently.<sup>10-13,17-21</sup> In  
55 particular, the joint use of conditioned structure function (SF) techniques<sup>17,24-26</sup> and Helmholtz-

56 Hodge decomposition<sup>27</sup> (HHD) appears to be a promising tool for acquiring fundamental  
 57 knowledge on turbulence in flames. The present work aims at applying this newly introduced  
 58 research tool<sup>28</sup> to DNS data of two turbulent lean H<sub>2</sub>/air flames with detailed chemistry.<sup>21,29-31</sup>

59 In the next section, research methods are presented. Results are reported and discussed in  
 60 Sect. III, followed by conclusions.

61 **II. RESEARCH METHODS**

62 **A. Helmholtz-Hodge decomposition**

63 HHD is a decomposition of a fluctuating velocity field  $\mathbf{u}'(\mathbf{x}, t)$  into two subfields: (i)  
 64 divergence-free solenoidal subfield  $\mathbf{u}'_s(\mathbf{x}, t)$  and (ii) curl-free potential subfield  $\mathbf{u}'_p(\mathbf{x}, t)$ , i.e.,

65 
$$\mathbf{u}' = \mathbf{u}'_s + \mathbf{u}'_p, \quad \nabla \cdot \mathbf{u}'_s = 0, \quad \nabla \times \mathbf{u}'_p = 0. \quad (1)$$

66 The last equality holds if  $\mathbf{u}'_p = \nabla\phi$ , where  $\phi(\mathbf{x}, t)$  is an arbitrary scalar function with  
 67  $\Delta\phi = \nabla \cdot \mathbf{u}'_p = \nabla \cdot \mathbf{u}'$  due to Eq. (1). HHD is of particular value for exploring the influence of  
 68 thermal expansion on the generation of potential velocity fluctuations in flames.

69 In the present work, two HHD methods were used: (i) conventional HHD<sup>27</sup> and (ii) natural  
 70 decomposition.<sup>32,33</sup> The former decomposition invokes the following constraint

$$\iiint_V \mathbf{u}'_s \cdot \mathbf{u}'_p d\mathbf{x} = 0, \quad (2)$$

71 which guarantees the additivity of the bulk kinetic energies of the solenoidal and potential  
 72 flow fields, i.e.

$$\iiint_V \mathbf{u}' \cdot \mathbf{u}' d\mathbf{x} = \iiint_V \mathbf{u}'_s \cdot \mathbf{u}'_s d\mathbf{x} + \iiint_V \mathbf{u}'_p \cdot \mathbf{u}'_p d\mathbf{x}. \quad (3)$$

73 Here,  $V$  designates the computational domain. Substitution of Eq. (1) into Eq. (2) yields

$$\begin{aligned} \iiint_V \mathbf{u}'_s \cdot \nabla \varphi d\mathbf{x} &= \iiint_V \nabla(\varphi \mathbf{u}'_s) d\mathbf{x} \\ &- \iint_S \varphi \nabla \cdot \mathbf{u}'_s d\mathbf{x} = \iint_S \varphi \mathbf{u}'_s \cdot \mathbf{n} dS - \iiint_V \varphi \nabla \cdot \mathbf{u}'_s d\mathbf{x}. \end{aligned} \quad (4)$$

74 Here,  $S$  is the boundary of the domain  $V$  and the unit vector  $\mathbf{n}$  is normal to this boundary. The  
 75 second (volume) integral vanishes, because  $\nabla \cdot \mathbf{u}'_s = 0$ . The first (surface) integral vanishes if  
 76  $\mathbf{u}'_s \cdot \mathbf{n} = 0$ . In this case, Eq. (2) holds and

$$\left. \frac{\partial \varphi}{\partial n} \right|_S = \mathbf{n} \cdot \nabla \varphi|_S = \mathbf{n} \cdot \mathbf{u}'_s \quad (5)$$

77 on the boundary  $S$ . The Neumann problem given by  $\Delta \varphi = \nabla \cdot \mathbf{u}'$  and Eq. (5) has a unique  
 78 solution for  $\varphi(\mathbf{x}, t)$ , i.e., the use of Eq. (2) or (5) makes the HHD unique.

79 The natural decomposition<sup>32,33</sup> deals with an extra vector-field  $\mathbf{w}(\mathbf{x}, t)$ , defined as follows:  
 80 (i)  $\mathbf{w}(\mathbf{x}, t) = \mathbf{u}(\mathbf{x}, t)$  for all  $\mathbf{x} \in V$ , and (ii)  $\mathbf{w}(\mathbf{x}, t)$  is extrapolated to the entire 3D space  $\mathbb{R}^3$   
 81 such that  $|\mathbf{w}(\mathbf{x}, t)| \rightarrow 0$  for  $|\mathbf{x}| \rightarrow \infty$ . This velocity field  $\mathbf{w}(\mathbf{x}, t)$  can be decomposed in the  
 82 entire space, i.e.,

$$\mathbf{w} = \nabla \Gamma + \nabla \times \mathbf{S}, \quad \mathbf{x} \in \mathbb{R}^3, \quad (6)$$

$$\Delta \Gamma = \nabla \cdot \mathbf{w}, \quad \mathbf{x} \in \mathbb{R}^3, \quad (7)$$

$$\nabla \times \nabla \times \mathbf{S} = \nabla \times \mathbf{w}, \quad \mathbf{x} \in \mathbb{R}^3. \quad (8)$$

83 Solutions to Eqs. (7)-(8) are unique

$$\Gamma(\mathbf{x}_0, t) = \iiint_{\mathbb{R}^3} G_\infty(\mathbf{x}, \mathbf{x}_0) \nabla \cdot \mathbf{w}(\mathbf{x}, t) d\mathbf{x}, \quad \mathbf{x}_0, \mathbf{x} \in \mathbb{R}^3, \quad (9)$$

$$\mathbf{S}(\mathbf{x}_0, t) = - \iiint_{\mathbb{R}^3} G_\infty(\mathbf{x}, \mathbf{x}_0) \nabla \times \mathbf{w}(\mathbf{x}, t) d\mathbf{x}, \quad \mathbf{x}_0, \mathbf{x} \in \mathbb{R}^3. \quad (10)$$

84 where  $G_{\infty}(\mathbf{x}, \mathbf{x}_0) = -1/(4\pi|\mathbf{x} - \mathbf{x}_0|)$  is the free-space Green's function in  $\mathbb{R}^3$ . Then,  
 85 integration in Eqs. (9)-(10) can be truncated outside the domain  $V$  by interpreting the  
 86 truncated integrals to be an external influence. Therefore,

$$\Gamma^*(\mathbf{x}_0, t) = \iiint_V G_{\infty}(\mathbf{x}, \mathbf{x}_0) \nabla \cdot \mathbf{u}(\mathbf{x}, t) d\mathbf{x}, \quad \mathbf{x}_0, \mathbf{x} \in V, \quad (11)$$

$$\mathbf{S}^*(\mathbf{x}_0, t) = - \iiint_V G_{\infty}(\mathbf{x}, \mathbf{x}_0) \nabla \times \mathbf{u}(\mathbf{x}, t) d\mathbf{x}, \quad \mathbf{x}_0, \mathbf{x} \in V. \quad (12)$$

87 Equation (1) with  $\mathbf{u}_s = \nabla \times \mathbf{S}^*$  and  $\mathbf{u}_p = \nabla \Gamma^*$  holds due to Eqs. (6)-(8).

88 Results yielded by the two HHD methods were compared in detail in an earlier paper.<sup>28</sup>  
 89 Since these results are hardly distinguishable within flame brushes, we will report results  
 90 obtained using the conventional HHD only.

#### 91 B. Conditioned structure functions

92 In fluid mechanics, the second-order SFs of a velocity field form the following tensor<sup>35</sup>

$$D_{ij}(\mathbf{x}, \mathbf{r}) \equiv \overline{[u_i(\mathbf{x} + \mathbf{r}, t) - u_i(\mathbf{x}, t)][u_j(\mathbf{x} + \mathbf{r}, t) - u_j(\mathbf{x}, t)]}, \quad (13)$$

93 where overbar designates averaging;  $u_i$  and  $u_j$  are  $i$ -th and  $j$ -th components, respectively, of  
 94 the velocity vector  $\mathbf{u} = \{u, v, w\}$ . Similarly to the turbulence spectrum, such SFs characterize  
 95 the distribution of turbulent energy over spatial scales.<sup>35</sup> Accordingly, the SFs are widely used  
 96 to study turbulence since a seminal work by Kolmogorov<sup>36</sup> and to model unresolved small-  
 97 scale effects in Large Eddy Simulations.<sup>37</sup>

98 When Eq. (13) is applied to a flame, the velocity differences are controlled not only by  
 99 turbulence, but also by thermal expansion effects. Such effects can be of primary importance  
 100 if the local flame front is between the points  $\mathbf{x}$  and  $\mathbf{x} + \mathbf{r}$ . Therefore, additional considerations  
 101 are needed to use SFs in combustion research. To this end, conditioned SFs were

102 independently introduced by Whitman et al.<sup>17</sup> and by Sabelnikov et al.<sup>24,25</sup> They applied two  
 103 different methods to DNS data of highly<sup>17</sup> and weakly<sup>24,25</sup> turbulent single-step chemistry  
 104 flames. Subsequently, the latter method was adopted<sup>26</sup> to analyze DNS data of single-step  
 105 chemistry flames, characterized by various ratios  $1 \leq u'/S_L \leq 10$  of root-mean-square (rms)  
 106 velocity,  $u'$ , to the laminar flame speed,  $S_L$ . Later, conditioned SFs were jointly used with  
 107 HHD<sup>28</sup> to explore thermal expansion effects in weakly turbulent single-step chemistry flames.  
 108 Yet, neither application of conditioned SFs to complex chemistry turbulent flames nor joint  
 109 application of conditioned SFs and HHD to moderately or highly turbulent combustion has  
 110 been reported.

111 Here, the conditioned second-order SFs of the velocity field are defined as follows<sup>24,25</sup>

$$112 \quad D_{ij}^{\alpha\beta}(\mathbf{x}, \mathbf{r}) \equiv \frac{1}{P_{\alpha\beta}} \overline{[u_i(\mathbf{x} + \mathbf{r}, t) - u_i(\mathbf{x}, t)][u_j(\mathbf{x} + \mathbf{r}, t) - u_j(\mathbf{x}, t)]I_\alpha(\mathbf{x}, t)I_\beta(\mathbf{x} + \mathbf{r}, t)}, \quad (14)$$

113 where superscripts  $\alpha$  and  $\beta$  refer to the mixture state; the indicator function  $I_u(\mathbf{x}, t)$  is equal  
 114 to unity if reactants are observed in point  $\mathbf{x}$  at instant  $t$  and vanishes otherwise;  $I_b(\mathbf{x}, t) = 1$   
 115 if products are observed in point  $\mathbf{x}$  at instant  $t$  and vanishes otherwise;  $I_r(\mathbf{x}) = 1$  if  $I_u(\mathbf{x}, t) =$   
 116  $I_b(\mathbf{x}, t) = 0$  and vanishes otherwise; and  $P_{\alpha\beta} = \overline{I_\alpha(\mathbf{x}, t)I_\beta(\mathbf{x} + \mathbf{r}, t)}$  are probabilities that the  
 117 mixture states  $\alpha$  and  $\beta$  are recorded in points  $\mathbf{x}$  and  $\mathbf{x} + \mathbf{r}$ , respectively, at the same instant.

118 Depending on  $\alpha$  and  $\beta$ , there are different conditioned SF tensors, with  $D_{ij}(\mathbf{x}, \mathbf{r})$  being  
 119 equal to  $\sum_{\alpha=1}^3 \sum_{\beta=1}^3 D_{ij}^{\alpha\beta}(\mathbf{x}, \mathbf{r})$  due to the identity of  $\sum_{\alpha=1}^3 \sum_{\beta=1}^3 I_\alpha(\mathbf{x})I_\beta(\mathbf{x} + \mathbf{r}) = 1$ . The  
 120 present work is restricted to the conditioned SFs  $D_{ij}^{uu}$  sampled in the cases where both  $\mathbf{x}$  and  
 121  $\mathbf{x} + \mathbf{r}$  are in the unburned gas. Such conditioned SFs appear to be of the most interest because  
 122 (i) a flame propagates into unburned gas and (ii) the velocity field upstream of the flame plays  
 123 a key role in the flame acceleration. Henceforth, the superscript  $uu$  will be omitted for brevity.

124 Since the DNS data analyzed here were obtained from statistically one-dimensional and  
 125 planar flames propagating from right to left along the  $x$ -direction in a box, the flow field is  
 126 assumed to be statistically isotropic and homogeneous in any plane  $x = \text{const}$ . Hence, the  
 127 present study is restricted to SFs found for points  $\mathbf{x} = \{x, y, z\}$  and  $\mathbf{x} = \{x, y + r_y, z + r_z\}$  that  
 128 belong to the same transverse plane  $x = \text{const}$ , i.e.,  $\mathbf{r} = \{0, r_y, r_z\}$ .

### 129 C. Numerical simulations and data analysis

130 As the DNS were discussed earlier,<sup>29-31</sup> only a brief description is given here. Lean (the  
 131 equivalence ratio  $\Phi=0.7$ )  $\text{H}_2$ -air turbulent flames propagating in a box were investigated by  
 132 (i) adopting a detailed (9 species, 23 reversible reactions) chemical mechanism<sup>38</sup> with the  
 133 mixture-averaged transport model and (ii) numerically solving unsteady three-dimensional  
 134 governing equations written in compressible form.

135 Along the flame propagation direction  $x$ , inflow and outflow characteristic boundary  
 136 conditions were set. Other boundaries were periodic. A divergence-free, isotropic,  
 137 homogeneous turbulent velocity field was generated using a pseudo spectral method<sup>39</sup> and  
 138 adopting the Passot-Pouquet spectrum.<sup>40</sup> The field was injected through the inlet (left)  
 139 boundary and decayed along the mean flow direction ( $x$ -axis).

140 **TABLE I.** Relevant parameters characterizing the DNS cases

	$u'/S_L$	$L_T/\delta_L$	$Re_T$	$Da$	$Ka_1$	$Ka_2$
W	0.7	14	227	20	33	0.5
H	5.0	14	1623	2.8	270	4

141 Ratios of the inflow value of the rms velocity to  $S_L$ , ratios of the most energetic length scale  
 142  $L_T$  of the Passot-Pouquet spectrum to the laminar flame thickness  $\delta_L = (T_b - T_u)/\max|\nabla T|$ ,  
 143 turbulent Reynolds number  $Re_T = u'L_T/\nu_u$ , Damköhler number  $Da = L_T S_L/(u'\delta_L)$ , and  
 144 two Karlovitz numbers are reported for the studied flames in Table 1. Here,  $S_L = 1.36$  m/s

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

Accepted to Phys. Fluids 10.1063/5.0096509

145 and  $\delta_L = 0.36$  mm have been computed using the same chemical mechanism under the  
 146 simulation conditions (temperature  $T_u = 300$  K and pressure  $P = 1$  atm);  $\nu_u$  is the kinematic  
 147 viscosity of unburned gas;  $Ka_1 = (\delta_L/\eta_K)^2$  and  $Ka_2 = \delta_L/(S_L\tau_K)$  have been evaluated  
 148 using (i) the Kolmogorov length scale  $\eta_K = \nu_u^{3/4}\bar{\epsilon}^{-1/4}$  and time scale  $\tau_K = \nu_u^{1/2}\bar{\epsilon}^{-1/2}$ , (ii)  
 149 the dissipation rate  $\bar{\epsilon} = 2\nu\overline{S_{ik}S_{ik}}$  averaged over the leading edge ( $\bar{c} = 0.01$ , with the  
 150 combustion progress variable  $c$  being defined using fuel mass fraction) of the mean flame  
 151 brush, and (iii) the rate-of-strain tensor  $S_{ik} = 0.5(\partial u_i/\partial x_k + \partial u_k/\partial x_i)$ .

152 The number  $Ka_1$  is significantly larger than  $Ka_2$ , because  $\delta_L = (T_b - T_u)/\max|\nabla T| \gg$   
 153  $\nu_u/S_L$  for the lean hydrogen-air laminar flame addressed here. Since (i) thicknesses of preheat  
 154 and reaction zones are comparable in this flame and (ii)  $Ka_1$  is large; both cases W and H are  
 155 associated with a significant probability of penetration of small-scale turbulent eddies into  
 156 local reaction zones.<sup>41</sup> Since  $Ka_2 > 1$  in flame H, it is also associated with substantial  
 157 probability of local combustion quenching.<sup>41</sup> Thus, as far as the influence of turbulence on  
 158 combustion is concerned, case H is definitely associated with highly turbulent burning.  
 159 Nevertheless, even in this case, the influence of combustion on turbulence can be significant,  
 160 as shown in Sect. III.

161 When analyzing the DNS data, firstly, transverse-averaged quantities  $\langle q \rangle(x, t)$  were  
 162 sampled at each instant. Secondly, these  $x$ -dependencies were mapped to  $\langle c \rangle$ -dependencies  
 163 using the averaged profiles  $\langle c \rangle(x, t)$ . Thirdly, mean values  $\bar{q}(\bar{c})$  of the quantity  $q$ , e.g., a  
 164 product of velocity differences in Eq. (14), were found by averaging  $\langle q \rangle[\langle c \rangle(x, t)]$  over time.

165 The probability  $P_{uu}(x, r)$  and the conditioned SFs determined by Eq. (14) were sampled  
 166 from points characterized by  $c(\mathbf{x}, t) < \epsilon \ll 1$ , with three such SFs being considered. Firstly,  
 167 the transverse SFs  $D_{xx,T}(x, r)$  for the axial velocity  $u'$  were computed by sampling  
 168  $[u'(\mathbf{x} + \mathbf{r}, t) - u'(\mathbf{x}, t)]^2$  from two sets of points: (i)  $\mathbf{r} = \{0, r, 0\}$  and (ii)  $\mathbf{r} = \{0, 0, r\}$ .

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

Accepted to Phys. Fluids 10.1063/5.0096509

169 Subsequently, the two samples were averaged. Secondly, the transverse SFs  $D_{yz,T}(x, r)$  for  
170 the transverse velocities  $v$  and  $w$  were obtained by sampling (i)  $[v'(\mathbf{x} + \mathbf{r}, t) - v'(\mathbf{x}, t)]^2$   
171 from points characterized by  $\mathbf{r} = \{0, 0, r\}$  and (ii)  $[w'(\mathbf{x} + \mathbf{r}, t) - w'(\mathbf{x}, t)]^2$  from points  
172 characterized by  $\mathbf{r} = \{0, r, 0\}$ . Subsequently, the two samples were averaged. Thirdly, the  
173 longitudinal SFs  $D_{yz,L}(x, r)$  for the transverse velocities were found by sampling (i)  
174  $[v'(\mathbf{x} + \mathbf{r}, t) - v'(\mathbf{x}, t)]^2$  from points characterized by  $\mathbf{r} = \{0, r, 0\}$  and (ii)  $[w'(\mathbf{x} + \mathbf{r}, t) -$   
175  $w'(\mathbf{x}, t)]^2$  from points characterized by  $\mathbf{r} = \{0, 0, r\}$ . Subsequently, the two samples were  
176 averaged. Solenoidal and potential conditioned SFs were obtained by separately applying such  
177 diagnostics to the solenoidal and potential velocity subfields, respectively.

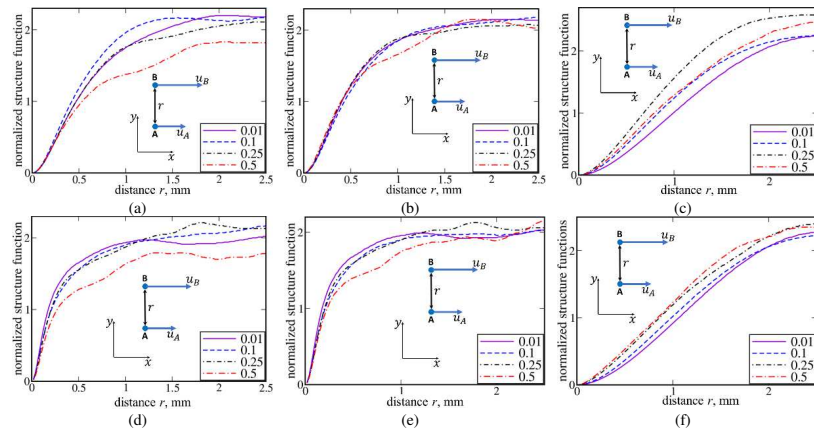
178 Reported in the following are dependencies of the conditioned SFs on the distance  $r$ ,  
179 sampled either inside a flame brush at various  $\bar{c}(x)$  or upstream of a flame brush at various  
180 distances  $\Delta x$  from it. The SFs were sampled adopting the threshold  $\epsilon = 0.05$  and the  
181 combustion progress variable  $c = 1 - Y_F/Y_{F,u}$  defined using fuel mass fraction. Weak  
182 sensitivity of the obtained results to  $\epsilon$  (either 0.01 or 0.05) or to the choice of combustion  
183 progress variable (temperature, water, and oxygen-based combustion progress variables were  
184 also adopted to analyze the same DNS data<sup>30</sup>) was checked.

### 185 III. RESULTS AND DISCUSSION

186 Figure 1 shows normalized transverse SFs  $D_{xx,T}[\bar{c}(x), r]$  for the total, solenoidal, and  
187 potential fluctuating axial velocity fields, conditioned to unburned gas in flames W (top row)  
188 and H (bottom row). The SFs have been sampled from various transverse planes characterized  
189 by different  $\bar{c}$  (see the figure legends). Henceforth, (i) each subfigure that reports a SF  
190 contains an insert, which sketches the SF type, and (ii) total, solenoidal, and potential SFs are

191 normalized using conditioned total, solenoidal, and potential rms velocities, respectively,  
 192 which are reported in Fig. 2.

193 At first glance, Figs. 1a and 1d do not show any significant and systematic change of the  
 194 total SF  $D_{xx,T}[\bar{c}(x), r]$  with  $\bar{c}$  if  $\bar{c} \leq 0.25$ . Such changes are not observed for the solenoidal  
 195 SFs either (Figs. 1b and 1e). Concerning the differences between  $D_{xx,T}[\bar{c}(x), r]$  sampled at  
 196  $\bar{c} \leq 0.25$  and  $\bar{c} = 0.5$  (red dotted-dashed lines), they can be attributed to decorrelation of  
 197 unburned gas motion in two points on the opposite sides of a flame segment. The probability  
 198 of finding such pairs of points is increased with the distance  $r$  and with  $\bar{c}$ , thus, making the  
 199  $D_{xx,T}[\bar{c} = 0.5, r]$ -curves less smooth at  $r > \delta_L$ .

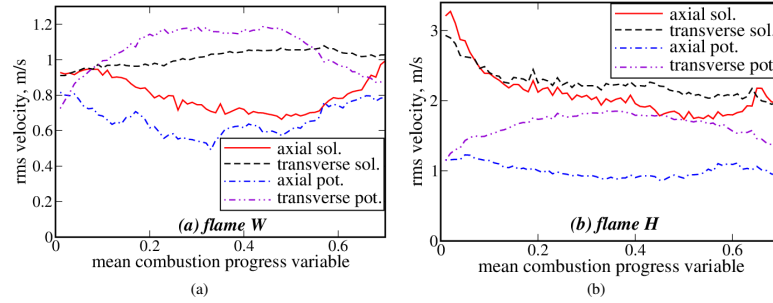


200 **FIG. 1.** Normalized transverse structure functions for the axial velocity, conditioned for unburned gas  
 201 and sampled from different transverse planes in flames W (top row) and H (bottom row). Values of  
 202 Reynolds-averaged combustion progress variable characterizing sampling planes are reported in the  
 203 legends. Results obtained by analyzing (a) and (d) total, (b) and (e) solenoidal, or (c) and (f) potential  
 204 velocity fields are reported in the left, middle, and right columns, respectively.  $\delta_L = 0.36$  mm.

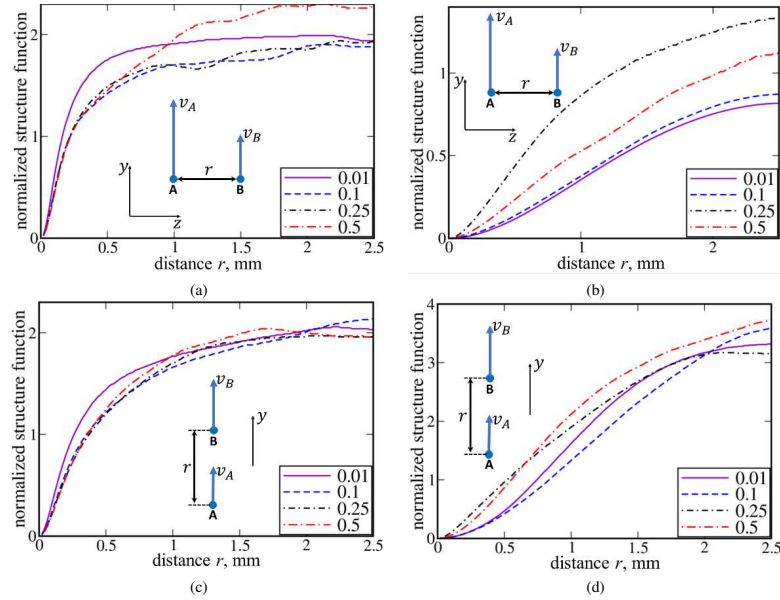
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

Accepted to Phys. Fluids 10.1063/5.0096509



205 **FIG. 2.** Variations of conditioned (i) axial solenoidal and potential rms velocities  
 206  $\langle u_s'^2 | c(\mathbf{x}, t) < 0.05 \rangle^{1/2}$  and  $\langle u_p'^2 | c(\mathbf{x}, t) < 0.05 \rangle^{1/2}$ , respectively, and (ii) transverse solenoidal and  
 207 potential rms velocities  $\langle 0.5(v_s'^2 + w_s'^2) | c(\mathbf{x}, t) < 0.05 \rangle^{1/2}$  and  $\langle 0.5(v_p'^2 + w_p'^2) | c(\mathbf{x}, t) < 0.05 \rangle^{1/2}$ ,  
 208 respectively, in flames (a) W and (b) H.



209 **FIG. 3.** Normalized (a) and (b) transverse structure functions  $D_{yz,T}[\bar{c}(x), r]$  (top row) or (c) and (d)  
 210 longitudinal structure functions  $D_{yz,L}[\bar{c}(x), r]$  (bottom row) for the transverse velocities, conditioned  
 211 to unburned gas and sampled from different transverse planes in flame H. Values of Reynolds-averaged  
 212 combustion progress variable characterizing sampling planes are reported in the legends. Results  
 213 obtained by analyzing (a) and (c) total or (b) and (d) potential fluctuating velocity fields are reported in  
 214 the left and right columns, respectively.  $\delta_L = 0.36$  mm.

215 On the contrary, the potential SF  $D_{xx,T}[\bar{c}(x), r]$  is increased with  $\bar{c}$  at  $\bar{c} \leq 0.25$  (Figs. 1c  
216 and 1f). The trend is well pronounced in case W (Fig. 1c). Even in the highly turbulent flame  
217 H (Fig. 1f), the trend is evident, but variations in  $D_{xx,T}[\bar{c}(x), r]$  with  $\bar{c}$  are less pronounced,  
218 thus indicating some reduction of the magnitude of thermal expansion effects in more intense  
219 turbulence. Moreover, the increase in the potential SF  $D_{xx,T}[\bar{c}(x), r]$  with  $\bar{c}$  (at  $\bar{c} \leq 0.25$ ) is  
220 evident at various distances  $r$ , including small distances  $r < \delta_L$ . Thus, Figs. 1c and 1f clearly  
221 indicate substantial influence of combustion-induced thermal expansion on all scales of  
222 potential velocity fluctuations in unburned gas within the mean flame brush. While the  
223 potential SFs are normalized using the potential rms velocities, Fig. 2 shows that the potential  
224 and solenoidal axial rms velocities are comparable in magnitude in flame W or H.

225 Significant variations of the conditioned potential SFs  $D_{yz,T}[\bar{c}(x), r]$  and  $D_{yz,L}[\bar{c}(x), r]$   
226 with  $\bar{c}$  are also seen in both cases, including the highly turbulent flame H (see Figs. 3b and  
227 3d, where such variations are strongly pronounced for  $0.1 \leq \bar{c} \leq 0.25$ , especially for  
228  $D_{yz,T}[\bar{c}(x), r]$ ). Again, differences between the conditioned potential SFs  $D_{yz,T}[\bar{c}(x), r]$  or  
229  $D_{yz,L}[\bar{c}(x), r]$  sampled at different  $\bar{c}$  are significant even at small distance  $r < \delta_L$ . Moreover,  
230 comparison of Figs. 3a and 3b or Figs. 3c and 3d shows an important qualitative difference  
231 between the total (left column in Fig. 3) and potential (right column) SFs; the potential SFs  
232 increase significantly slower with distance  $r$  and do not level off even at large  $r$ . The same  
233 qualitative difference is observed when comparing Figs. 1a and 1c or Figs. 1d and 1f.

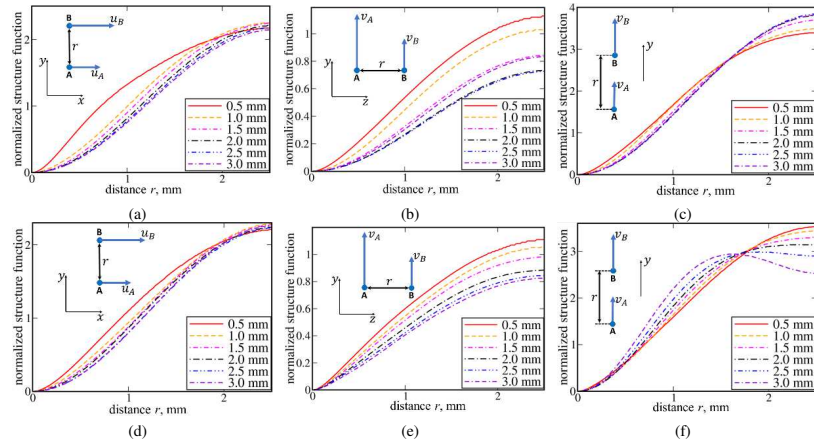
234 As shown above, the spatial structure of potential velocity fluctuations differs substantially  
235 from that of the incoming solenoidal turbulent fluctuations. Such changes of the spatial  
236 structure of the fluctuating velocity field in unburned gas within flame brush are not  
237 negligible, because conditioned solenoidal and potential rms velocities are of the same order  
238 even in the highly turbulent flame H (Fig. 2b). Also note that the conditioned total SFs

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

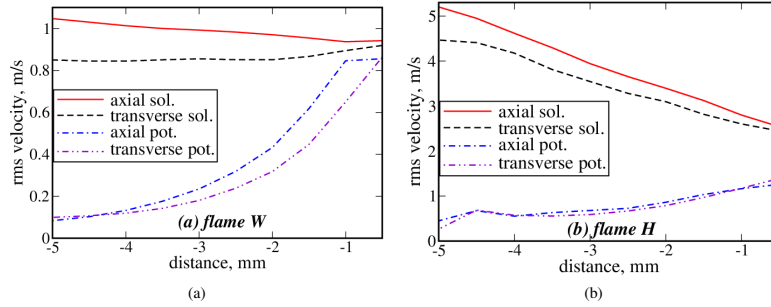
Accepted to Phys. Fluids 10.1063/5.0096509

239  $D_{yz,T}[\bar{c}(x), r]$  and  $D_{yz,L}[\bar{c}(x), r]$  sampled at  $\bar{c} = 0.01$  differ from their counterparts sampled  
 240 at  $0.1 \leq \bar{c}$ , even at small distance  $r < \delta_L$  (Figs. 3a and 3c), further indicating the importance  
 241 of the influence of thermal expansion on turbulence in flames.



242 **FIG. 4.** Normalized potential structure functions (a) and (d)  $D_{xx,T}(x, r)$  (left column), (b) and (e)  
 243  $D_{yz,T}(x, r)$  (middle column), or (c) and (f)  $D_{yz,L}(x, r)$  (right column) sampled upstream of flames (a-  
 244 c) W (top row) and (d-f) H (bottom row) at different distances from their leading edges, specified in  
 245 the legends.  $\delta_L = 0.36$  mm.

246 For the potential velocity field, such an influence is well pronounced even upstream ( $\bar{c} <$   
 247 0.01) of the flame brushes in both cases (Fig. 4), with the field being highly anisotropic.  
 248 Indeed, on the one hand, variations of potential SFs with the distance  $\Delta x$  (see legends) from  
 249 the flame leading edge are most pronounced for  $D_{yz,T}(x, r)$  (Figs. 4b and 4e) and least  
 250 pronounced for  $D_{yz,L}(x, r)$  (Figs. 4c and 4f). On the other hand, at large  $r$ ,  $D_{yz,L}(x, r)$  is  
 251 significantly larger than  $D_{yz,T}(x, r)$ . Moreover, the anisotropy of the potential SFs is  
 252 significantly more pronounced than the weak anisotropy of potential rms velocities (Fig. 5),  
 253 which were used to normalize the SFs. This demonstrates that simple diagnostic tools (rms  
 254 velocities) are unable to reveal the explored thermal expansion effects.



255 **FIG. 5.** Variations of (i) axial solenoidal and potential rms velocities  $(\overline{u_s'^2})^{1/2}$  and  $(\overline{u_p'^2})^{1/2}$ ,  
 256 respectively, and (ii) transverse solenoidal and potential rms velocities  $[0.5(\overline{v_s'^2} + \overline{w_s'^2})]^{1/2}$  and  
 257  $[0.5(\overline{v_p'^2} + \overline{w_p'^2})]^{1/2}$ , respectively, upstream of flames (a) W and (b) H.

258 Comparison of Figs. 4a and 4d or 4b and 4e indicates that variations in the potential  
 259 transverse structure function  $D_{xx,T}(x, r)$  or  $D_{yz,T}(x, r)$ , respectively, with  $\Delta x$  are more  
 260 pronounced in flame W, thus, again implying some reduction of the magnitude of thermal  
 261 expansion effects in more intense turbulence. However, comparison of Figs. 4c and 4f shows  
 262 the opposite trend for the potential longitudinal structure function  $D_{yz,L}(x, r)$ .

263 Figure 4 also shows that the potential SFs  $D_{yz,T}(x, r)$  and  $D_{yz,L}(x, r)$  do not approach 2 at  
 264 large  $r$ . To the contrary, in homogeneous turbulence,  $D_{ii}(\mathbf{r}) = 2\overline{u_i'^2}$  at large distances  $|\mathbf{r}|$   
 265 because the correlation between velocities vanishes.<sup>35</sup> Thus, Fig. 4 indicates that combustion-  
 266 induced transverse velocity fluctuations correlate at large distances. Difference between  
 267 transverse velocities  $v(x, y, z, t)$  and  $v(x, y + r, z, t)$  could be statistically positive even at  
 268 large  $r$ , because thermal expansion in a flame tongue can push unburned gas to the opposite  
 269 directions on the opposite sides of the tongue. As a result, within a flame brush,  $D_{yz,L}(x, r)$   
 270 could be significantly larger than 2 at large  $r$  (Fig. 3d). Figures 4c and 4f imply that such flow  
 271 perturbations can expand upstream of a flame brush due to pressure waves.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

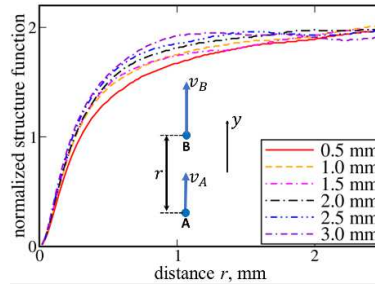
Accepted to Phys. Fluids 10.1063/5.0096509

272 Figure 5 shows that, upstream of a flame brush, the potential rms velocity increases with  
273 decreasing distance from the flame leading edge (from left to right), with the effect being more  
274 pronounced in case W. As a result, potential and solenoidal rms velocities are almost equal  
275 or, at least, comparable at  $|\Delta x| = 0.5$  mm in case W or H, respectively. While comparable  
276 magnitudes of the potential and solenoidal rms velocities at  $|\Delta x| = 0.5$  mm in case H stem  
277 partially from the spatial decay of the solenoidal velocity fluctuations, the Karlovitz numbers  
278 reported in Table 1 have been evaluated using the dissipation rate  $\bar{\epsilon}$  sampled at  $|\Delta x| = 0$ .  
279 Thus, despite the turbulence decay, case H deals with a highly turbulent flame. Moreover,  
280 even if an increase in the potential rms velocities with decreasing  $|\Delta x|$  seems to be more  
281 pronounced in flame W, these rms velocities are larger in case H at  $|\Delta x| = 0$ .

282 The simulated influence of combustion-induced thermal expansion on turbulence upstream  
283 of a premixed flame brush is not unexpected. This effect stems from rapid propagation of  
284 pressure perturbations from the flame to upstream flow of unburned reactants. In a laminar  
285 flow, such pressure perturbations are well known to cause hydrodynamic instability of a  
286 laminar premixed flame,<sup>42</sup> or self-similar acceleration of a large-scale flame kernel ignited in  
287 a quiescent mixture.<sup>43</sup> In turbulent flows, some influence of a premixed flame on upstream  
288 turbulence was documented in a few experimental papers,<sup>44,45</sup> but the phenomenon requires  
289 more studies. It has not yet been explored by another research group by analyzing DNS data  
290 obtained from premixed turbulent flames or by adopting HHD techniques.

291 Finally, Fig. 6 shows that even solenoidal SFs sampled upstream of flame H vary with the  
292 distance  $|\Delta x|$ , with the effect being most pronounced at  $\delta_L < r < 3\delta_L$  and  $|\Delta x| \leq 1$  mm. A  
293 flame can affect the upstream solenoidal velocity field due to the potential velocity  
294 contribution to vortex-stretching term in vorticity transport equation,<sup>10-13</sup> but such secondary

295 effects are less pronounced than the direct influence of combustion-induced pressure  
 296 perturbations on the potential velocity.



297  
 298 **FIG. 6.** Normalized solenoidal structure functions  $D_{yz,L}(x, r)$  sampled upstream of flame H.

#### 299 IV. CONCLUSIONS

300 Two advanced research tools, (i) Helmholtz-Hodge decomposition of fluctuating velocity  
 301 into divergence-free solenoidal and irrotational potential components and (ii) conditioned  
 302 structure functions, were jointly used to explore the influence of combustion-induced thermal  
 303 expansion on turbulence by analyzing DNS data of complex chemistry, lean  $H_2$ /air, turbulent  
 304 flames. While these two methods were earlier<sup>28</sup> applied to explore such an influence, the major  
 305 advancement of the present work consists of showing importance of thermal expansion effects  
 306 in highly turbulent flames. Moreover, the present analysis has yielded new insights into the  
 307 influence of thermal expansion on turbulence, as follows.

308 Firstly, results show that thermal expansion effects can seem to be weakly pronounced  
 309 when analyzing conditioned SFs for the entire or solenoidal velocity field, but well  
 310 pronounced when exploring potential SFs. Moreover, while the potential SFs clearly show  
 311 significant anisotropy of velocity field upstream of flame brush, such a trend is not revealed  
 312 when analyzing the potential rms velocities. Thus, the use of a single diagnostic technique is  
 313 not sufficient to prove that thermal expansion effects are of minor importance.

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

Accepted to Phys. Fluids 10.1063/5.0096509

314 Secondly, under conditions of the present study, thermal expansion substantially changes  
315 not only SFs conditioned to unburned gas within mean flame brush, but also SFs sampled  
316 upstream of the flame brush. Such effects are more pronounced for the potential SFs but are  
317 also notable for the solenoidal SFs. These results show that a premixed flame is stretched by  
318 turbulence that differs substantially from turbulence far upstream of the flame. While the  
319 documented effects of combustion-induced thermal expansion on the flow are more  
320 pronounced in the flame W associated with a less intense turbulence, they play a role in the  
321 highly turbulent flame H as well.

322 The reported findings call for development of advanced models of turbulence in flames,  
323 which allow for the discussed thermal expansion effects and can predict them at least  
324 qualitatively. The joint use of HHD and conditioned SF methods appears to be a promising  
325 tool for acquiring fundamental knowledge that is required for development of such models.  
326 Since comparison of the present results obtained from complex-chemistry moderately and  
327 highly turbulent flames with results obtained earlier<sup>28</sup> from two single-step-chemistry weakly  
328 turbulent flames does not reveal any significant effect resulting from complex combustion  
329 chemistry, it is recommended to perform future DNS studies of the influence of premixed  
330 combustion on turbulence by employing simpler chemical kinetic mechanisms in favor of  
331 computational efficiency to cover a wider range of turbulent flame characteristics ( $u'/S_L$ ,  
332  $L_T/\delta_L$ ,  $Ka$ ,  $Da$ ,  $Re_T$ , etc.). On the contrary complex chemistry effects should be addressed  
333 when exploring the influence of turbulence on combustion.

#### 334 ACKNOWLEDGEMENTS

335 VAS gratefully acknowledges the financial support provided by ONERA. ANL gratefully  
336 acknowledges the financial support provided by Combustion Engine Research Center  
337 (CERC). FEHP and HGI were sponsored by King Abdullah University of Science and

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

Accepted to *Phys. Fluids* 10.1063/5.0096509

338 Technology (KAUST). Computational resources for the DNS calculations were provided by  
339 the KAUST Supercomputing Laboratory.

#### 340 AUTHOR DECLARATIONS

##### 341 Conflict of Interest

342 The authors have no conflicts to disclose.

#### 343 DATA AVAILABILITY

344 The data that support the findings of this study are available from the corresponding author  
345 upon reasonable request.

#### 346 REFERENCES

- 347 <sup>1</sup>B. Karlovitz, D. W. Denniston, and F. E. Wells, "Investigation of turbulent flames," *J. Chem. Phys.*  
348 **19**, 541 (1951).  
349 <sup>2</sup>A. C. Scurllock and J. H. Grover, "Propagation of turbulent flames," *Proc. Combust. Inst.* **4**, 645 (1953).  
350 <sup>3</sup>C. Dopazo, L. Cifuentes, and N. Chakraborty, "Vorticity budgets in premixed combustng turbulent  
351 flows at different Lewis numbers," *Phys. Fluids* **29**, 045106 (2017).  
352 <sup>4</sup>A. N. Lipatnikov, V. A. Sabelnikov, S. Nishiki, and T. Hasegawa, "Combustion-induced local shear  
353 layers within premixed flamelets in weakly turbulent flows," *Phys. Fluids* **30**, 085101 (2018).  
354 <sup>5</sup>A. N. Lipatnikov, V. A. Sabelnikov, S. Nishiki, and T. Hasegawa, "Does flame-generated vorticity  
355 increase turbulent burning velocity?" *Phys. Fluids* **30**, 081702 (2018).  
356 <sup>6</sup>A. N. Lipatnikov, V. A. Sabelnikov, S. Nishiki, and T. Hasegawa, "A direct numerical simulation  
357 study of the influence of flame-generated vorticity on reaction-zone-surface area in weakly turbulent  
358 premixed combustion" *Phys. Fluids* **31**, 055101 (2019).  
359 <sup>7</sup>A. R. Varma, U. Ahmed, and N. Chakraborty "Effects of body forces on vorticity and enstrophy  
360 evolutions in turbulent premixed flames," *Phys. Fluids* **33**, 035102 (2021).  
361 <sup>8</sup>J. F. MacArt and M. E. Mueller, "Damköhler number scaling of active cascade effects in turbulent  
362 premixed combustion," *Phys. Fluids* **33**, 035103 (2021).  
363 <sup>9</sup>N. Chakraborty, C. Kasten, U. Ahmed, and M. Klein, "Evolutions of strain rate and dissipation rate of  
364 kinetic energy in turbulent premixed flames," *Phys. Fluids* **33**, 125132 (2021).  
365 <sup>10</sup>A. N. Lipatnikov and J. Chomiak, "Effects of premixed flames on turbulence and turbulent scalar  
366 transport," *Prog. Energy Combust. Sci.* **36**, 1 (2010).  
367 <sup>11</sup>V. A. Sabelnikov and A. N. Lipatnikov, "Recent advances in understanding of thermal expansion  
368 effects in premixed turbulent flames," *Annu. Rev. Fluid Mech.* **49**, 91 (2017).  
369 <sup>12</sup>N. Chakraborty, "Influence of thermal expansion on fluid dynamics of turbulent premixed combustion  
370 and its modeling implications," *Flow Turbul. Combust.* **106**, 753 (2021).  
371 <sup>13</sup>A. M. Steinberg, P. E. Hamlington, and X. Zhao, "Structure and dynamics of highly turbulent  
372 premixed combustion," *Prog. Energy Combust. Sci.* **85**, 100900 (2021).  
373 <sup>14</sup>P. E. Hamlington, A. Y. Poludnenko, and E. S. Oran, "Interactions between turbulence and flames in  
374 premixed reacting flows," *Phys. Fluids* **23**, 125111 (2011).  
375 <sup>15</sup>B. Bobbitt, S. Lapointe, and G. Blanquart, "Vorticity transformation in high Karlovitz number  
376 premixed flames," *Phys. Fluids* **28**, 015101 (2016).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

Accepted to Phys. Fluids 10.1063/5.0096509

- 377 <sup>16</sup>B. Bobbitt and G. Blanquart, "Vorticity isotropy in high Karlovitz number premixed flames," Phys.  
378 Fluids **28**, 105101 (2016).
- 379 <sup>17</sup>S. H. R. Whitman, C. A. Z. Towery, A. Y. Poludnenko, and P. E. Hamlington, "Scaling and collapse  
380 of conditional velocity structure functions in turbulent premixed flames," Proc. Combust. Inst. **37**,  
381 2527 (2019).
- 382 <sup>18</sup>J. Lee, J. F. MacArt, M. E. Mueller, "Heat release effects on the Reynolds stress budgets in turbulent  
383 premixed jet flames at low and high Karlovitz numbers," Combust. Flame **216**, 1 (2020).
- 384 <sup>19</sup>R. Darragh, C. A. Z. Towery, A. Y. Poludnenko, and P. E. Hamlington, "Particle pair dispersion and  
385 eddy diffusivity in a high-speed premixed flame," Proc. Combust. Inst. **38**, 2845 (2021).
- 386 <sup>20</sup>J. Lee and M. E. Mueller, "Closure modeling for the conditional Reynolds stresses in turbulent  
387 premixed combustion," Proc. Combust. Inst. **38**, 3031 (2021).
- 388 <sup>21</sup>V. A. Sabelnikov, A. N. Lipatnikov, S. Nishiki, H. L. Dave, F. E. Hernández-Pérez, W. Song, and H.  
389 G. Im, "Dissipation and dilatation rates in premixed turbulent flames," Phys. Fluids **33**, 035112  
390 (2021).
- 391 <sup>22</sup>A. Kazbekov and A. M. Steinberg, "Flame- and flow-conditioned vorticity transport in premixed swirl  
392 combustion," Proc. Combust. Inst. **38**, 2949 (2021).
- 393 <sup>23</sup>A. Kazbekov and A. M. Steinberg, "Physical space analysis of cross-scale turbulent kinetic energy  
394 transfer in premixed swirl flames," Combust. Flame **229**, 111403 (2021).
- 395 <sup>24</sup>V. A. Sabelnikov, A. N. Lipatnikov, S. Nishiki, and T. Hasegawa, "Application of conditioned  
396 structure functions to exploring influence of premixed combustion on two-point turbulence  
397 statistics," Proc. Combust. Inst. **37**, 2433 (2019).
- 398 <sup>25</sup>V. A. Sabelnikov, A. N. Lipatnikov, S. Nishiki, and T. Hasegawa, "Investigation of the influence of  
399 combustion-induced thermal expansion on two-point turbulence statistics using conditioned  
400 structure functions," J. Fluid Mech. **867**, 45 (2019).
- 401 <sup>26</sup>P. Brearley, U. Ahmed, N. Chakraborty, and A. Lipatnikov, "Statistical behaviors of conditioned two-  
402 point second-order structure functions in turbulent premixed flames in different combustion  
403 regimes," Phys. Fluids **31**, 115109 (2019).
- 404 <sup>27</sup>A. J. Chorin and J. E. Marsden, *A Mathematical Introduction to Fluid Mechanics* (Springer, Berlin,  
405 Germany, 1993).
- 406 <sup>28</sup>V. A. Sabelnikov, A. N. Lipatnikov, N. Nikitin, S. Nishiki, and T. Hasegawa, "Application of  
407 Helmholtz-Hodge decomposition and conditioned structure functions to exploring influence of  
408 premixed combustion on turbulence upstream of the flame," Proc. Combust. Inst. **38**, 3077 (2021).
- 409 <sup>29</sup>D. H. Wacks, N. Chakraborty, M. Klein, P. G. Arias, and H. G. Im, "Flow topologies in different  
410 regimes of premixed turbulent combustion: A direct numerical simulation analysis," Phys. Rev.  
411 Fluids **1**, 083401 (2016).
- 412 <sup>30</sup>A. N. Lipatnikov, V. A. Sabelnikov, F. E. Hernández-Pérez, W. Song, and H. G. Im, "A priori DNS  
413 study of applicability of flamelet concept to predicting mean concentrations of species in turbulent  
414 premixed flames at various Karlovitz numbers," Combust. Flame **222**, 370 (2020).
- 415 <sup>31</sup>A. N. Lipatnikov, V. A. Sabelnikov, F. E. Hernández-Pérez, W. Song, and H. G. Im, "Prediction of  
416 mean radical concentrations in lean hydrogen-air turbulent flames at different Karlovitz numbers  
417 adopting a newly extended flamelet-based presumed PDF," Combust. Flame **226**, 248 (2021).
- 418 <sup>32</sup>H. Bhatia, G. Norgard, V. Pascucci, and P.-T. Bremer, "The Helmholtz-Hodge decomposition – a  
419 survey," IEEE Trans. Vis. Comput. Graph. **19**, 1386 (2013).
- 420 <sup>33</sup>H. Bhatia, V. Pascucci, and P.-T. Bremer, "The natural Helmholtz-Hodge decomposition for open-  
421 boundary flow analysis," IEEE Trans. Vis. Comput. Graph. **20**, 1566 (2014).
- 422 <sup>34</sup>V. A. Sabelnikov, A. N. Lipatnikov, N. Nikitin, S. Nishiki, and T. Hasegawa, "Solenoidal and  
423 potential velocity fields in weakly turbulent premixed flames," Proc. Combust. Inst. **38**, 3087 (2021).
- 424 <sup>35</sup>A. S. Monin and A. M. Yaglom, *Statistical Fluid Mechanics: Mechanics of Turbulence*, vol. 2 (MIT  
425 Press, Cambridge, Massachusetts, 1971).
- 426 <sup>36</sup>A. N. Kolmogorov, "Local structure of turbulence in an incompressible fluid at very high Reynolds  
427 numbers," Dokl. Akad. Nauk SSSR **30**, 299 (1941).
- 428 <sup>37</sup>M. Lesieur, O. Metais, and P. Comte, *Large-Eddy Simulations of Turbulence* (Cambridge University  
429 Press, Cambridge, U.K., 2005).

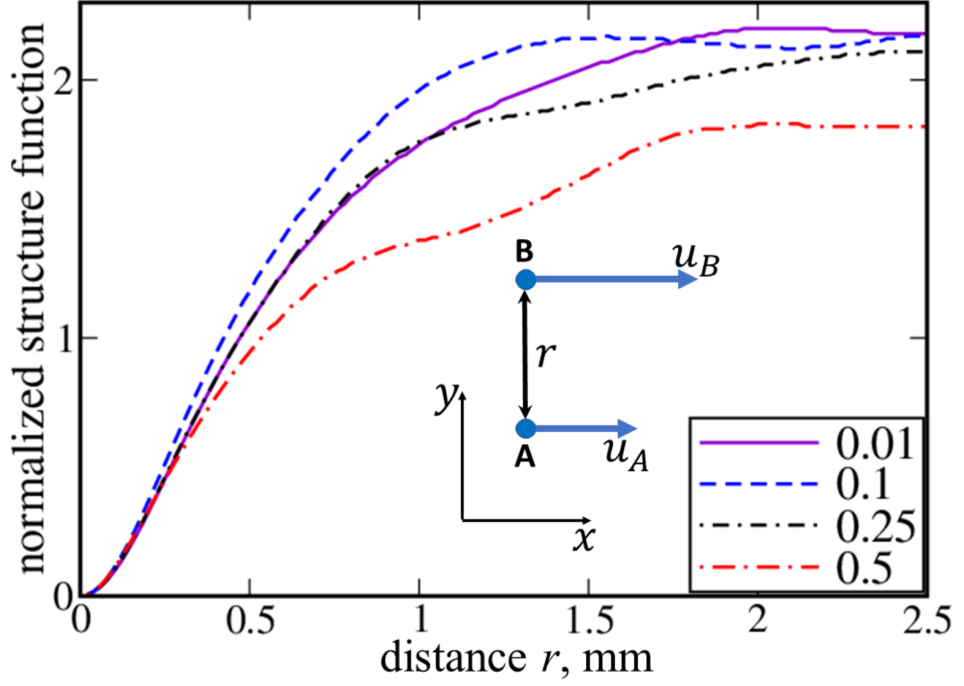
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/5.0096509

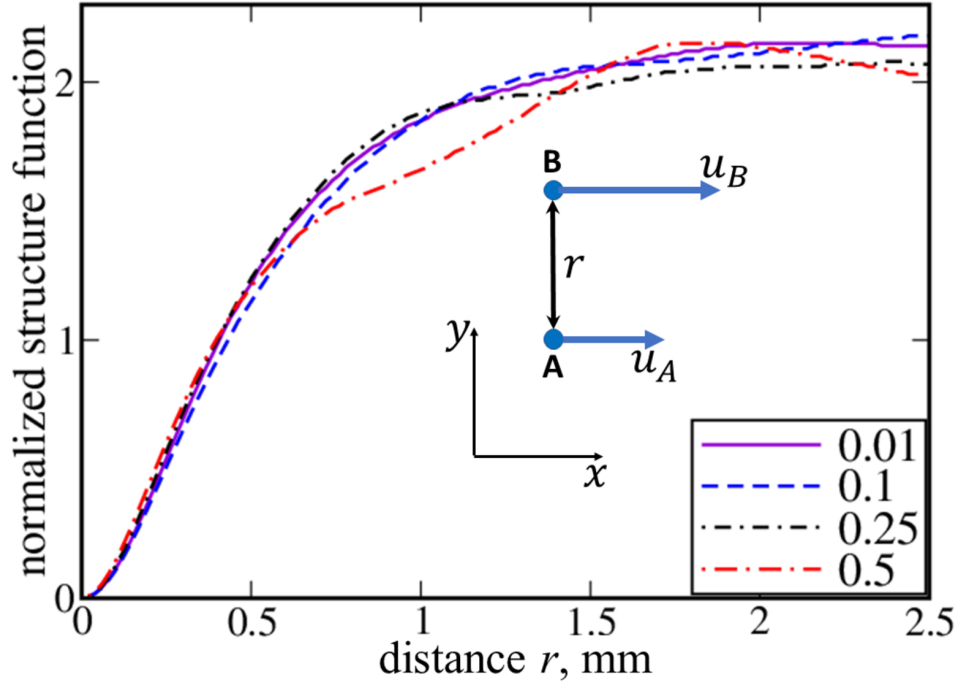
Accepted to Phys. Fluids 10.1063/5.0096509

- 430 <sup>38</sup>M. P. Burke, M. Chaos, Y. Ju, F. L. Dryer, and S. J. Klippenstein, "Comprehensive H<sub>2</sub>/O<sub>2</sub> kinetic  
431 model for high-pressure combustion," *Int. J. Chem. Kinet.* **44**, 444 (2012).  
432 <sup>39</sup>R. S. Rogallo, Numerical experiments in homogeneous turbulence, NASA Technical Memorandum  
433 81315, NASA Ames Research Center, California, 1981.  
434 <sup>40</sup>T. Passot and A. Pouquet, "Numerical simulation of compressible homogeneous flows in the turbulent  
435 regime," *J. Fluid Mech.* **181**, 441 (1987).  
436 <sup>41</sup>N. Peters, *Turbulent Combustion* (Cambridge Univ. Press, Cambridge, UK, 2000).  
437 <sup>42</sup>Ya. B. Zel'dovich, G. I. Barenblatt, V. B. Librovich, and G. M. Makhviladze, *The Mathematical*  
438 *Theory of Combustion and Explosions* (Consultants Bureau, New York, 1985).  
439 <sup>43</sup>Y. A. Gostintsev, A. G. Istratov, and Y. V. Shulenin, "Self-similar propagation of a free turbulent  
440 flame in mixed gas mixtures," *Combust. Explos. Shock Waves* **24**, 563 (1988).  
441 <sup>44</sup>B. D. Videto and D. A. Santavicca, D.A., "Flame-turbulence interactions in a freely-propagating,  
442 premixed flame," *Combust. Sci. Technol.* **70**, 47 (1990).  
443 <sup>45</sup>J. Furukawa, Y. Noguchi, T. Hirano, and F. Williams, "Anisotropic enhancement of turbulence in  
444 large-scale, low-intensity turbulent premixed propane-air flames," *J. Fluid Mech.* **462**, 209 (2002).

This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
 PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

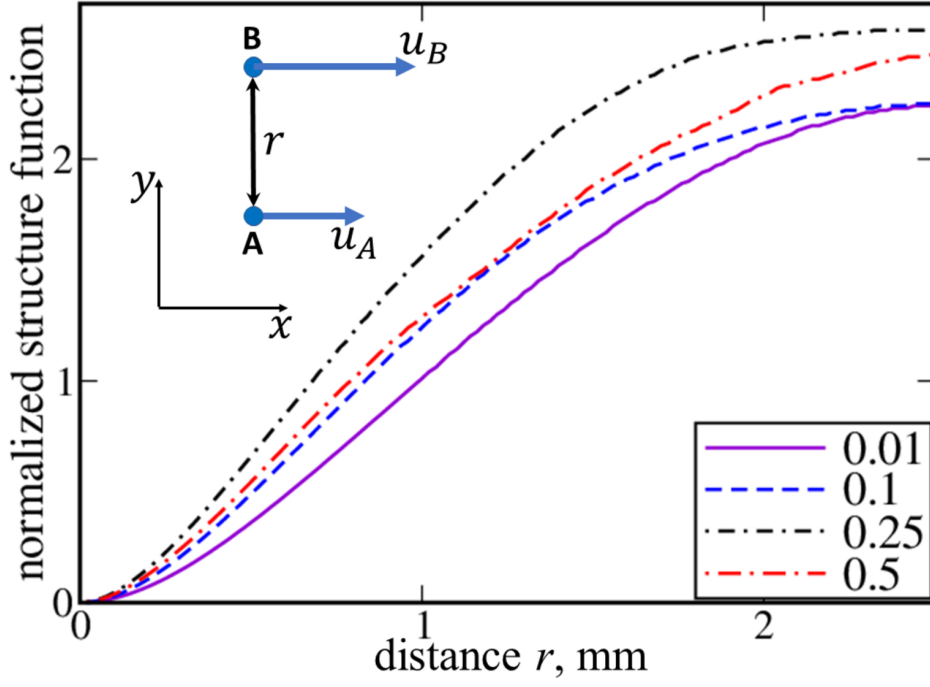


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
 PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

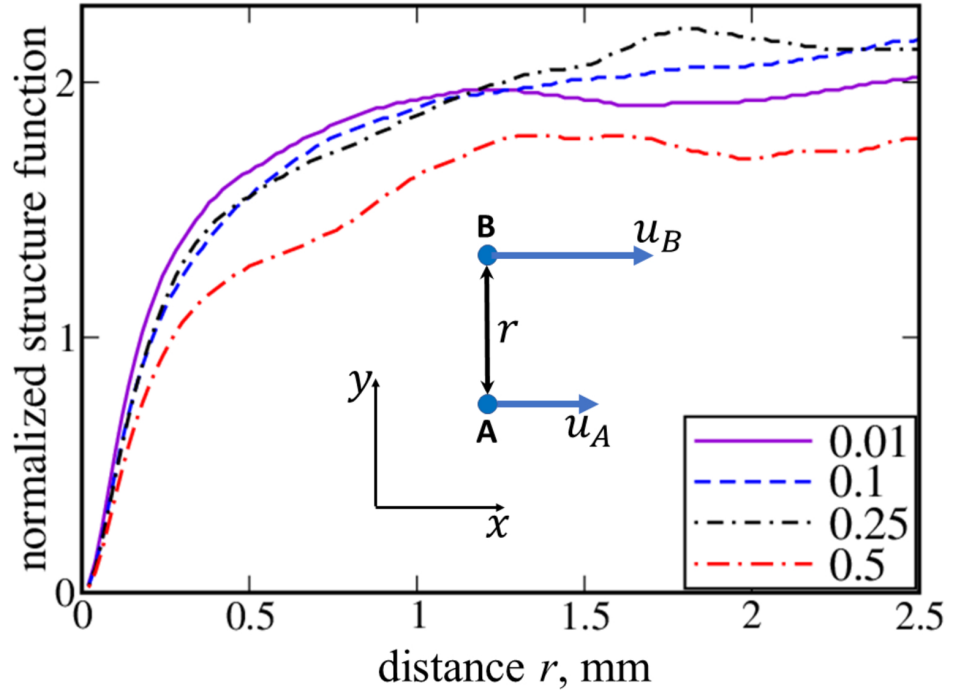


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

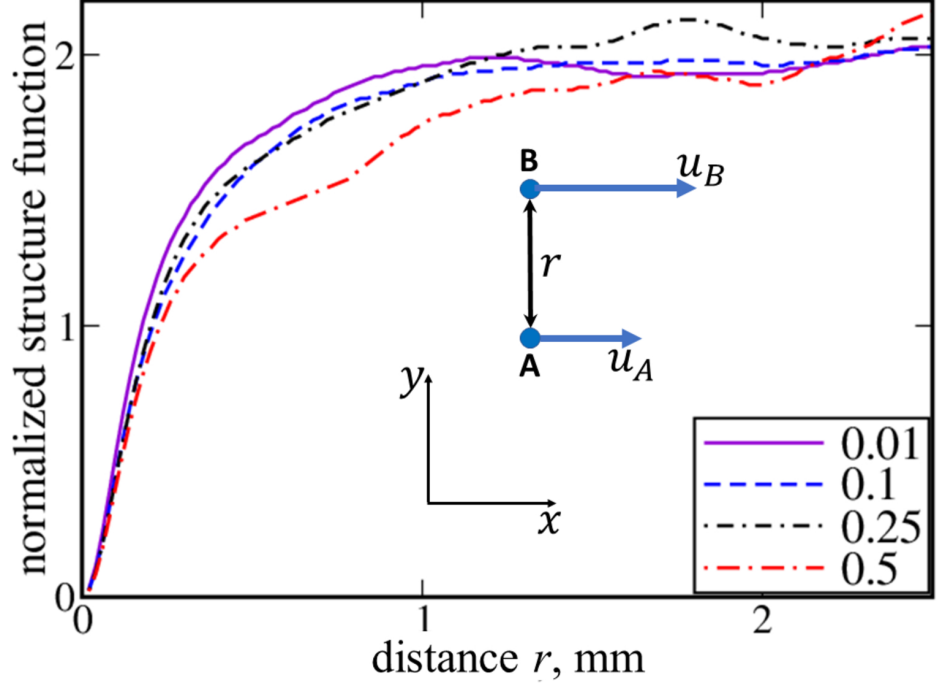


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
 PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



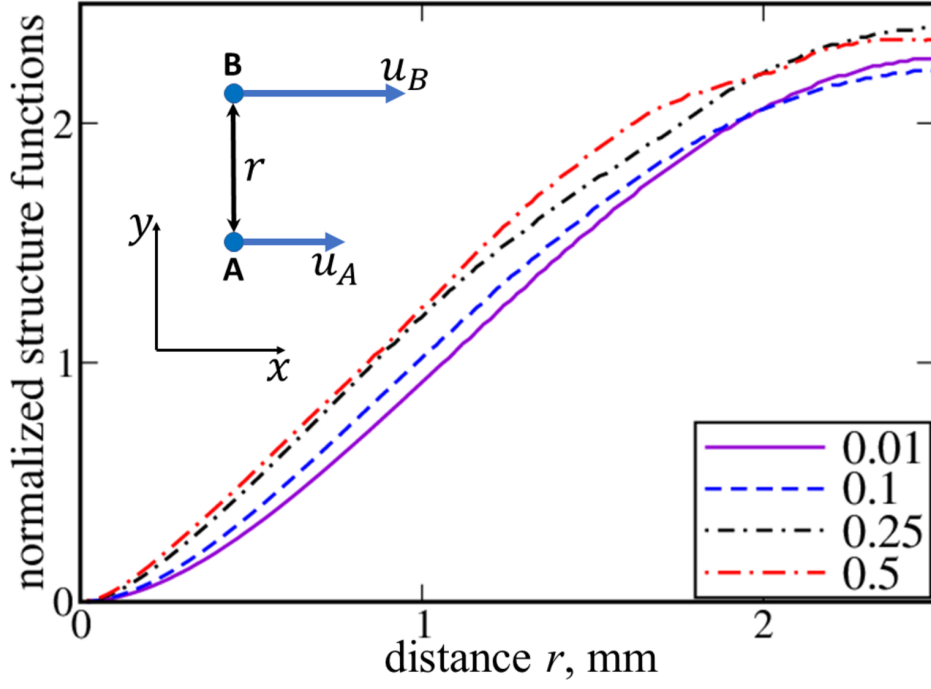
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



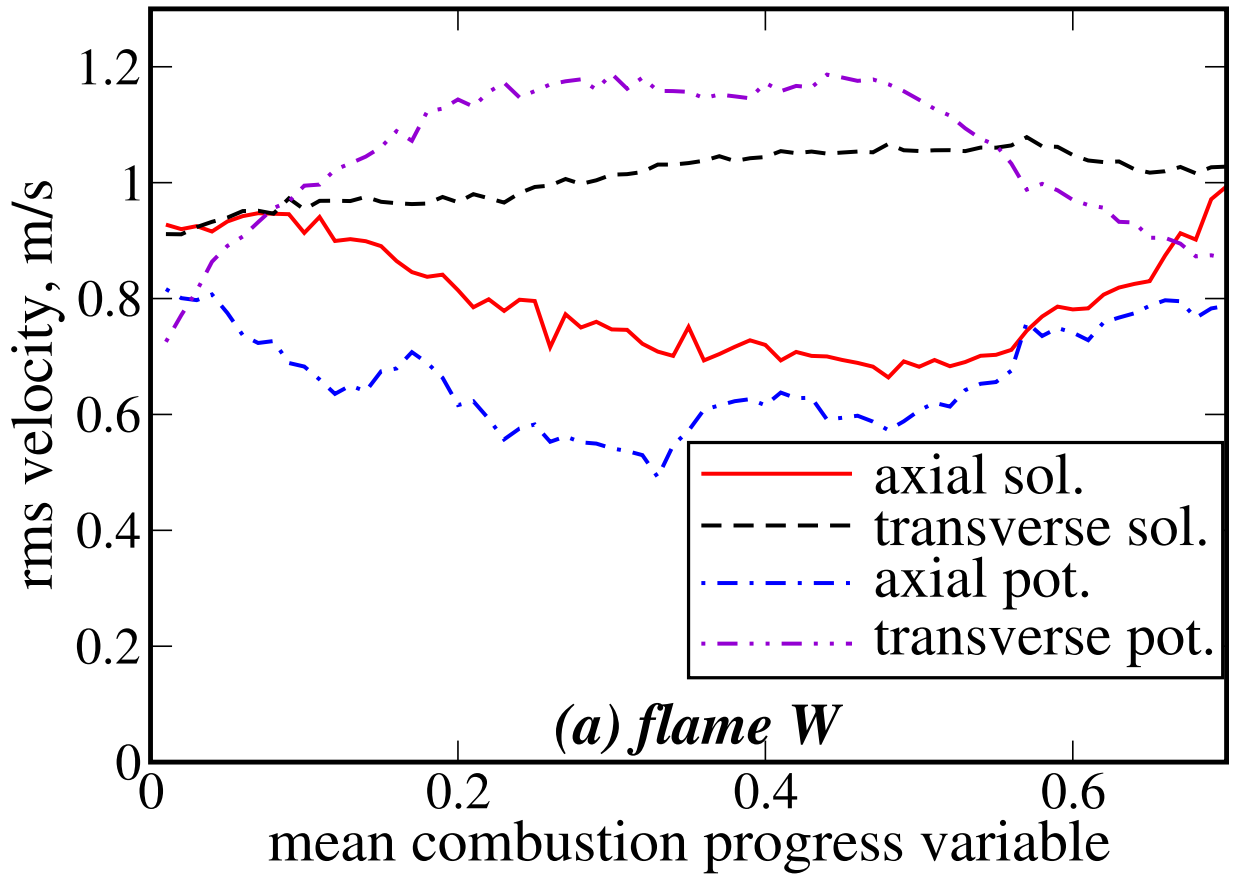
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

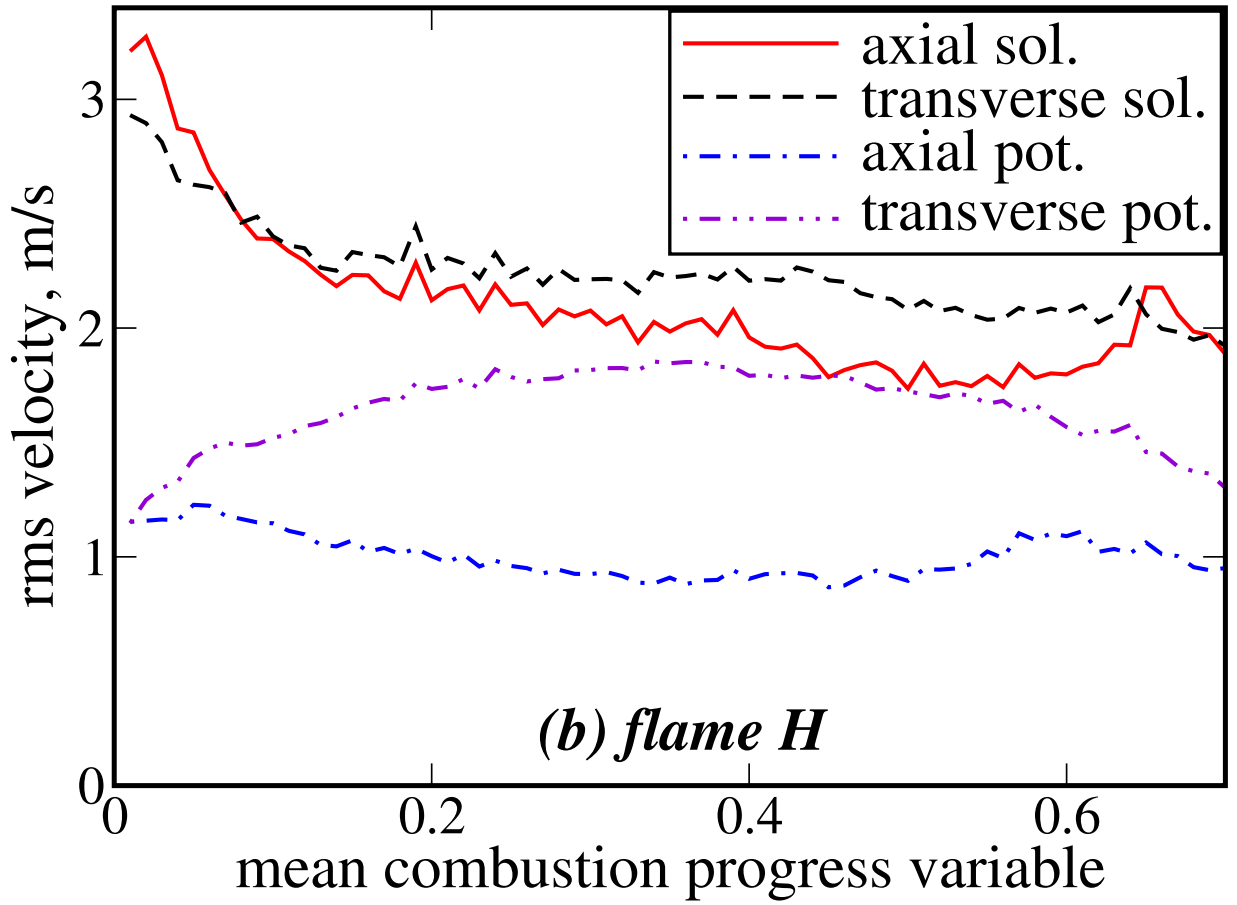


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

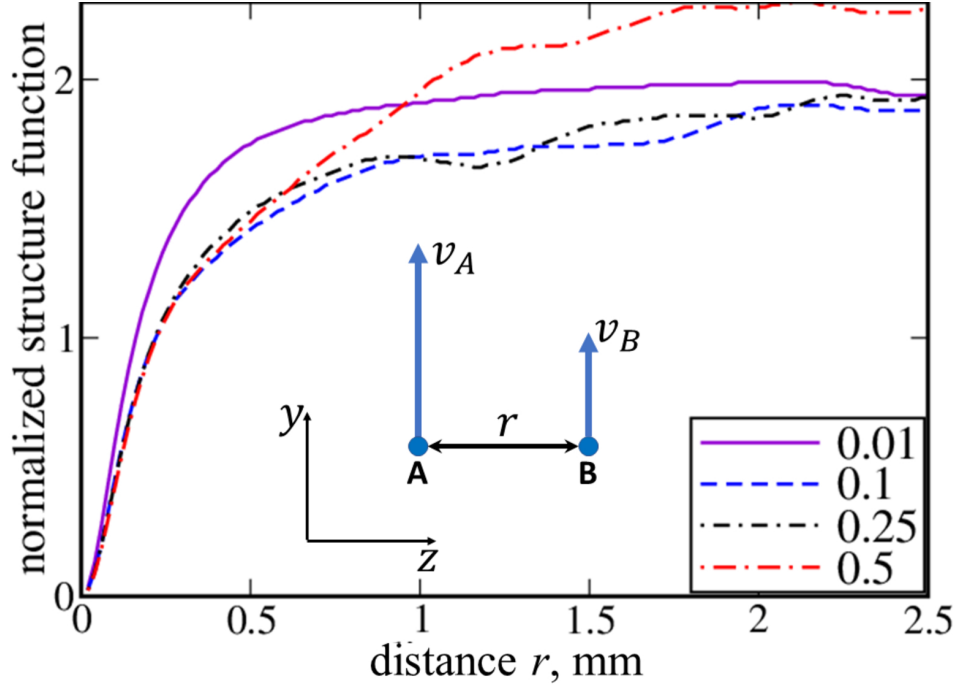
PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

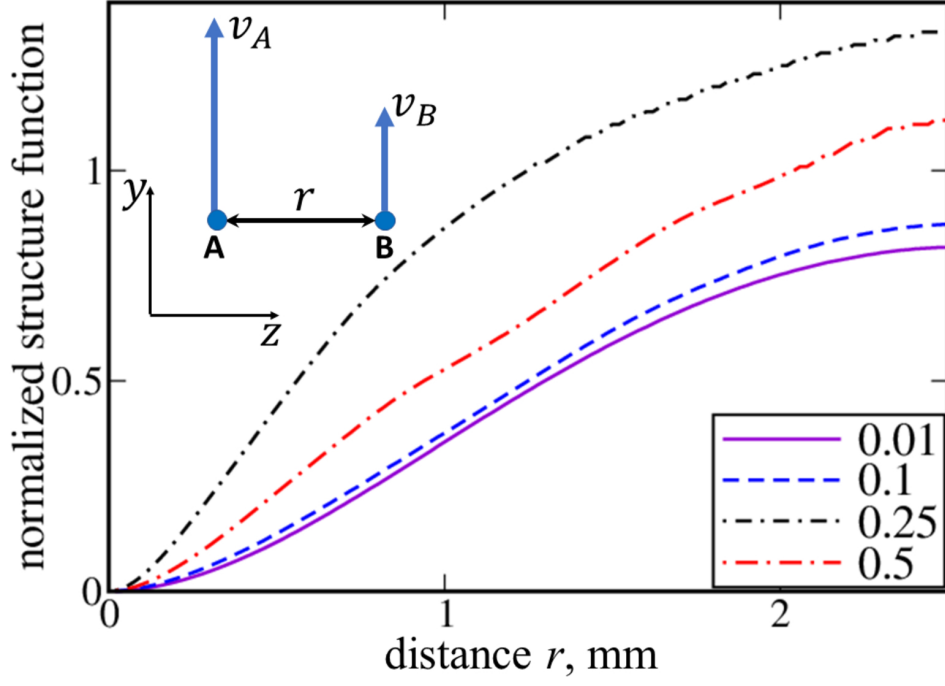


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
 PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

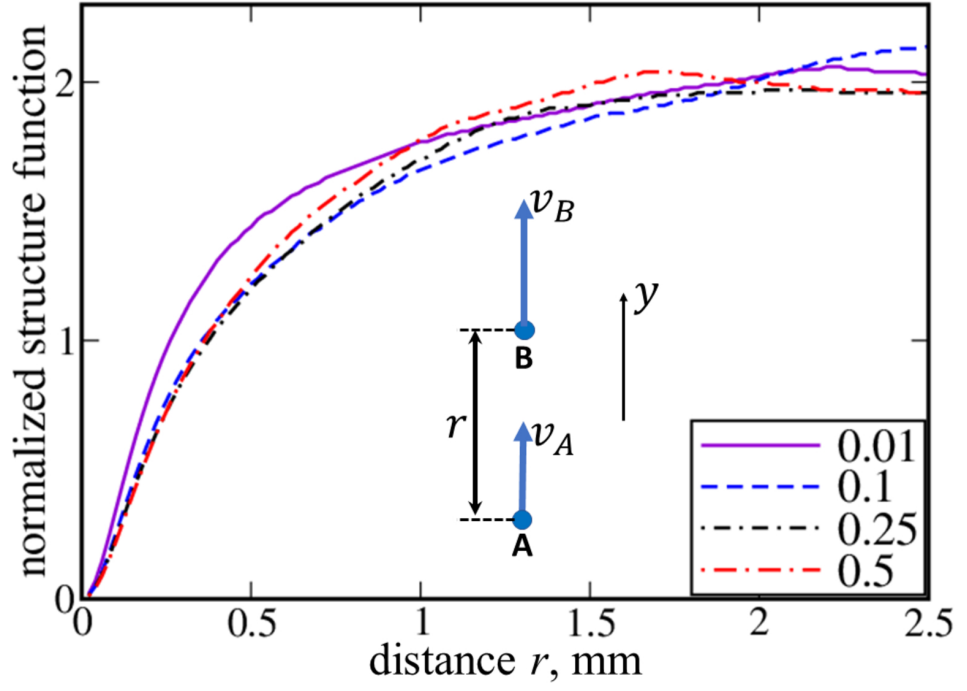


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

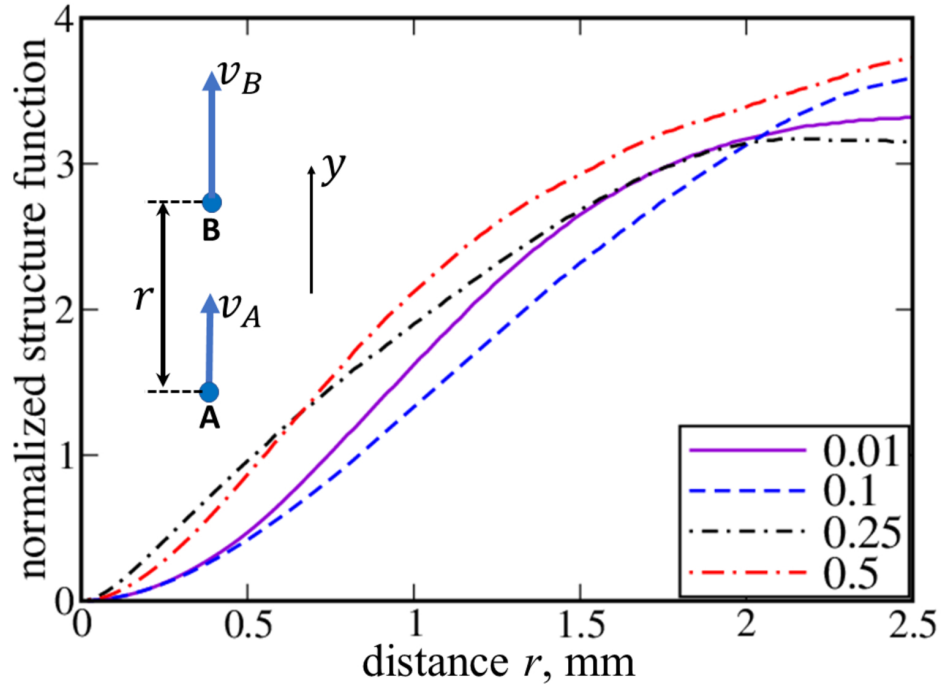


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
 PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



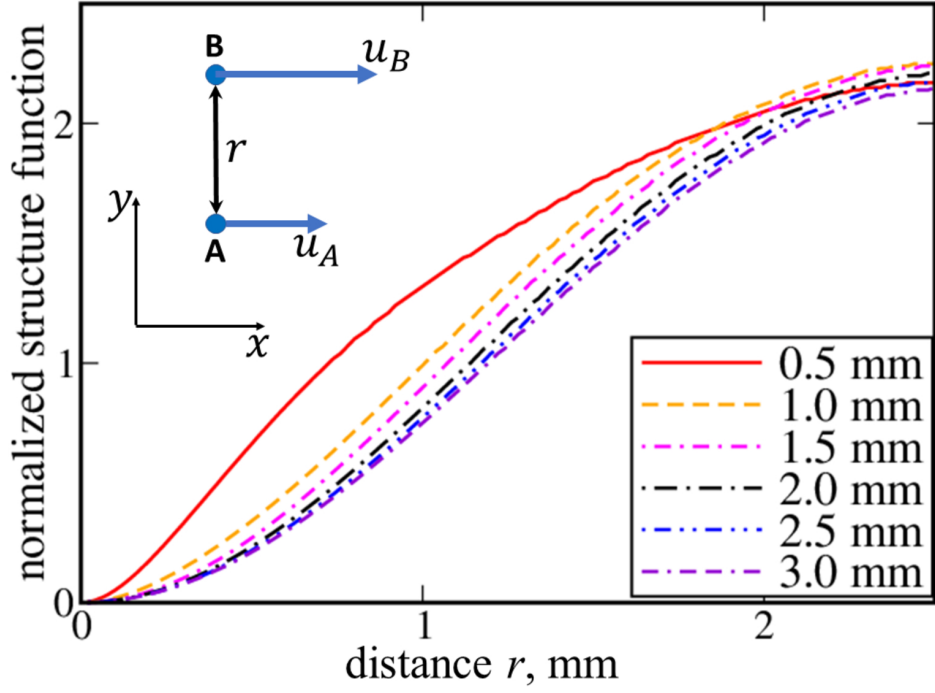
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



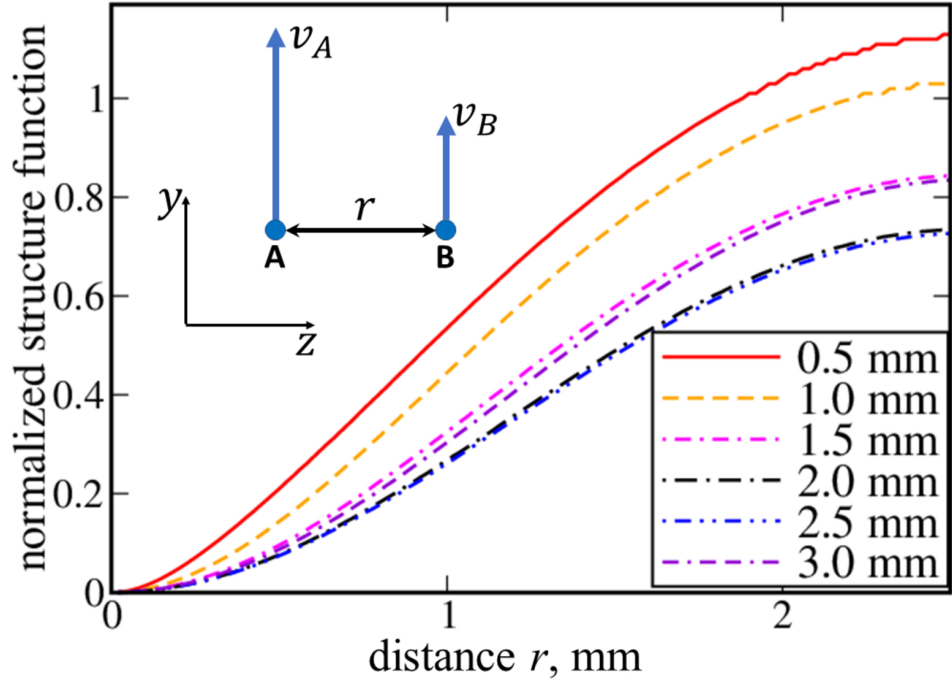
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



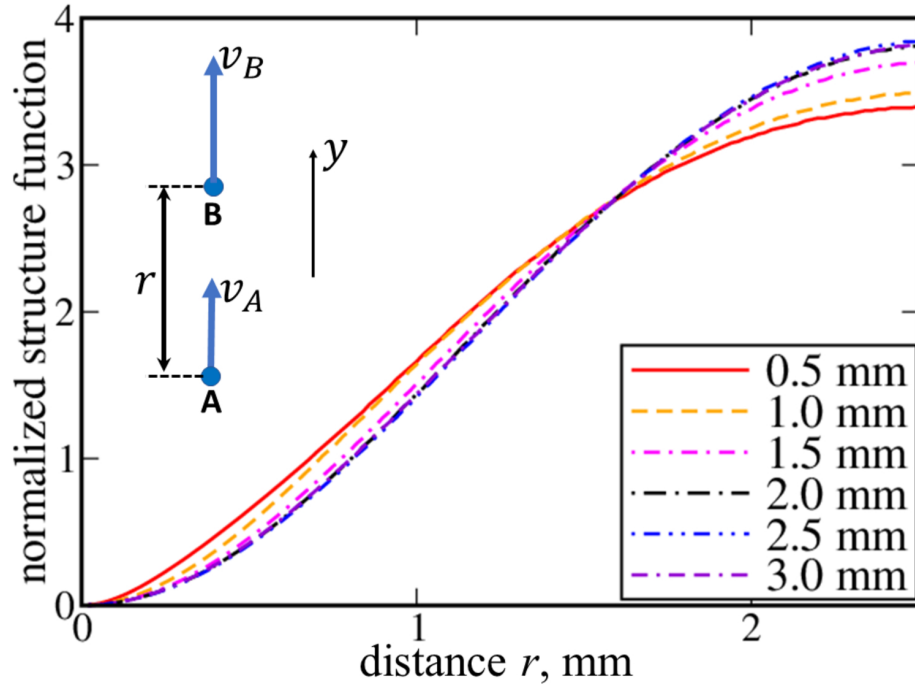
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



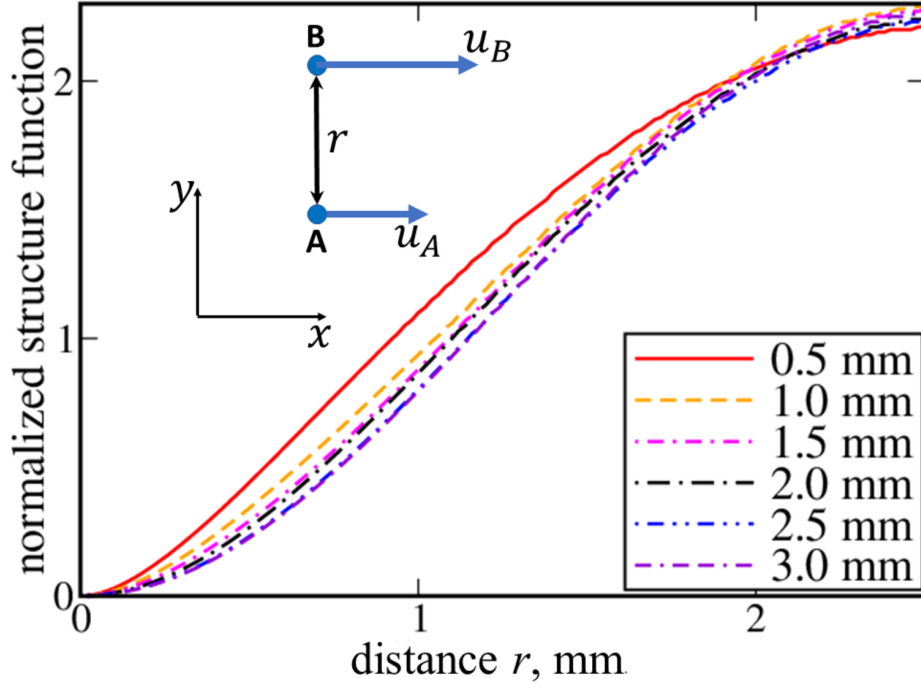
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



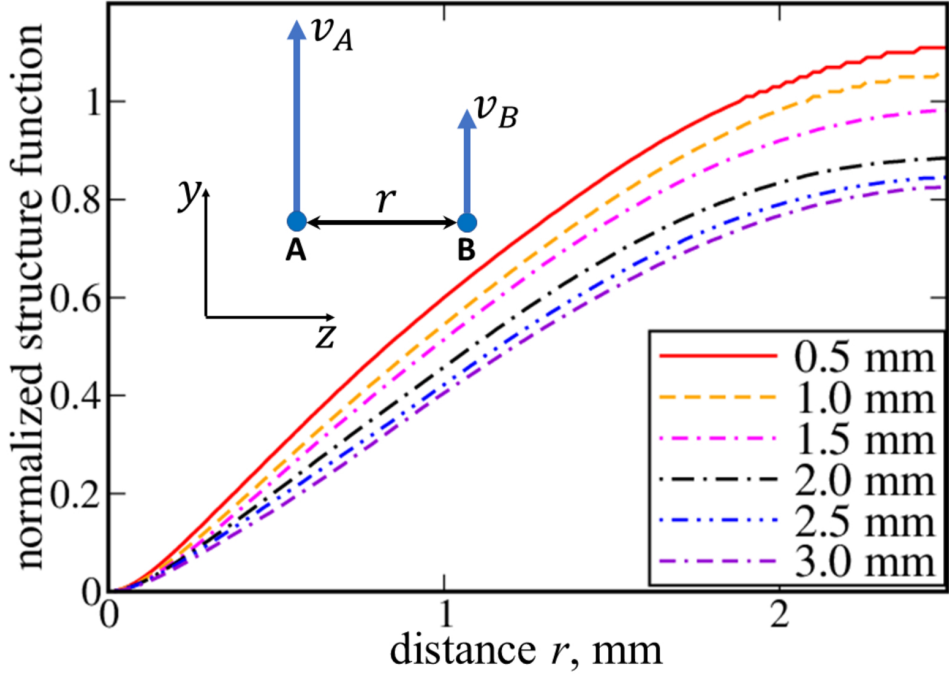
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

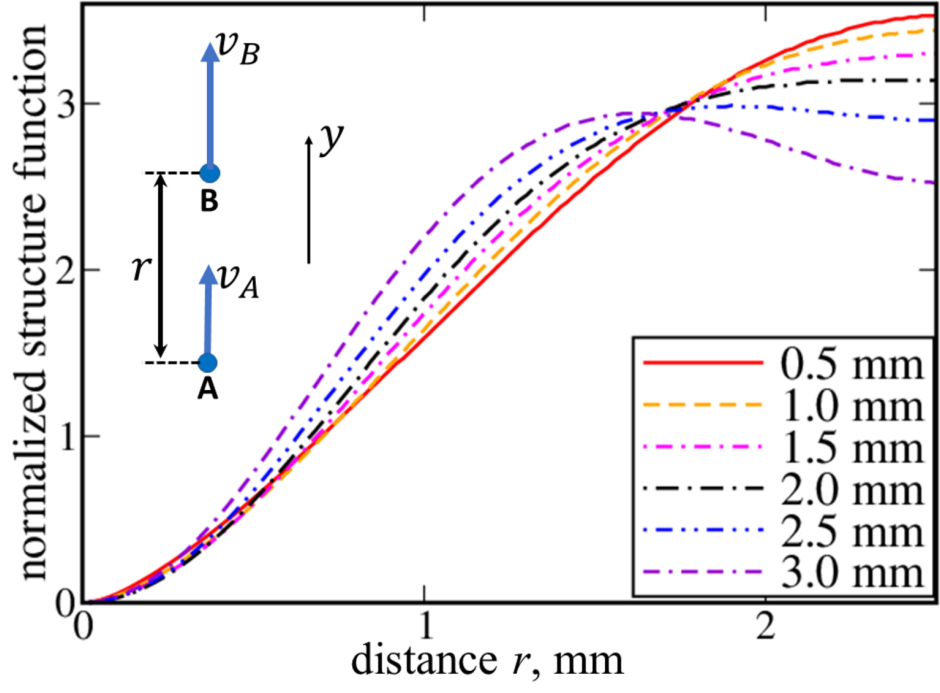


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

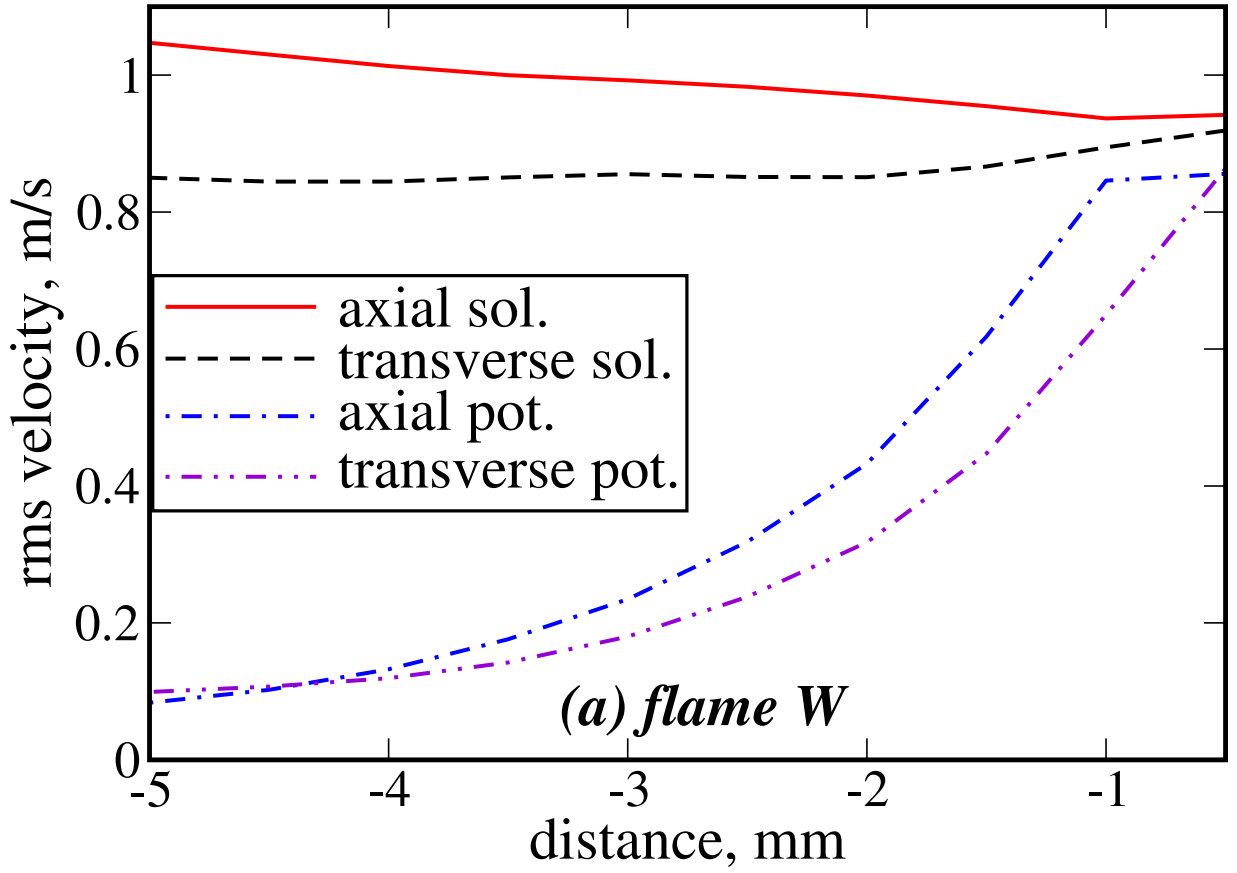


This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.  
 PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



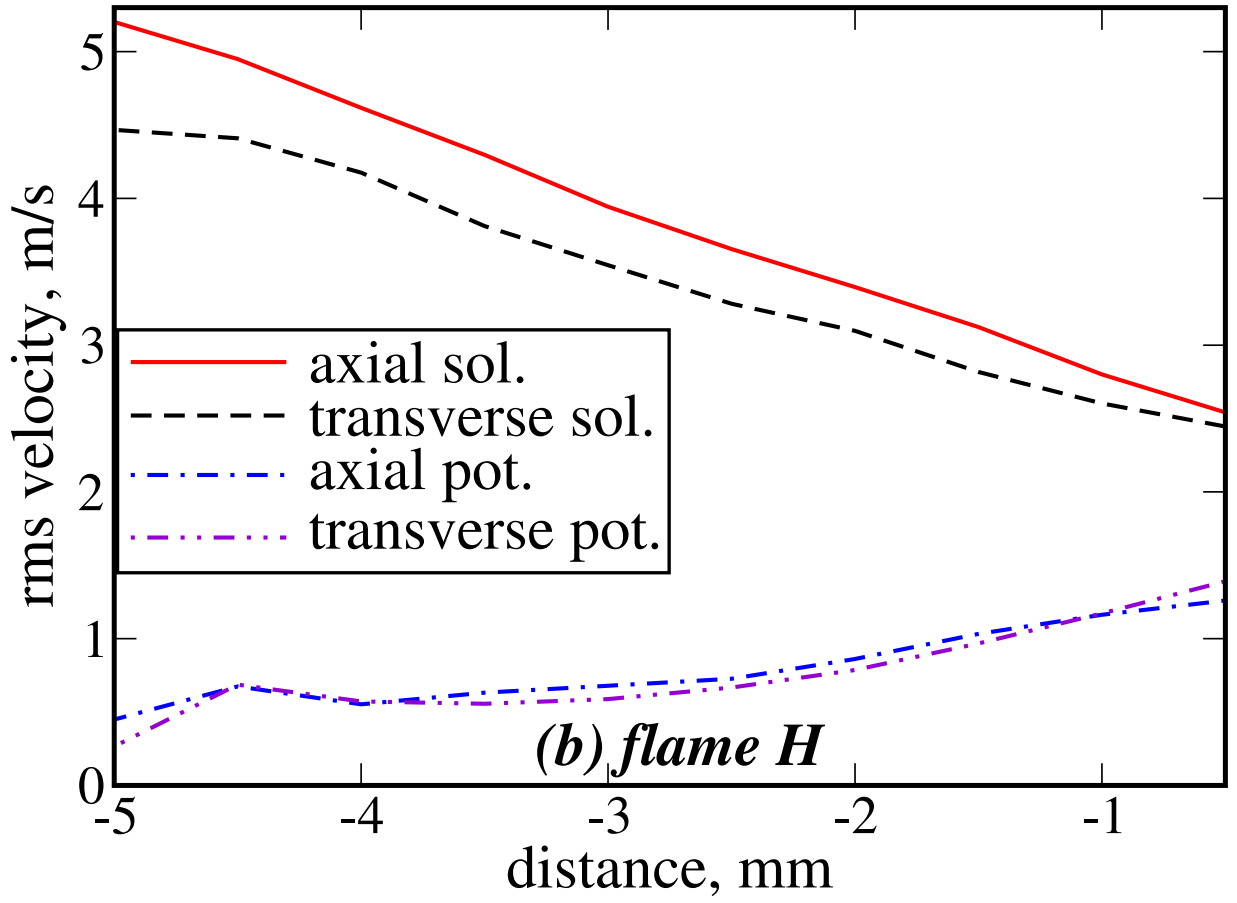
This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509



This is the author's peer reviewed, accepted manuscript. However, the online version of record will be different from this version once it has been copyedited and typeset.

PLEASE CITE THIS ARTICLE AS DOI: 10.1063/1.50096509

