Superstructures in a diffusion torch

V V Lemanov, V V Lukashov and K A Sharov

Kutateladze Institute of Thermal Physics, SB RAS, 630090, Russia, Novosibirsk, 1 Lavrentyev Ave.

E-mail: lemanov@itp.nsc.ru

Abstract. The paper presents the experimental results for isothermal flows (CO2, propane) and diffusion flames (C3H8 or H2 mixed with CO2). Optical method of PIV (Particle Image Velocimetry) and flow visualization are used. The paper considers the features of the effect of vortex superstructures on an attached diffusion plume. When superstructures interact with the flame front, the question of choosing the determining scales becomes ambiguous. Apparently, the features of the perturbation interaction can depend on the acoustic characteristics of the flows and, accordingly, on the nature of the density distribution in the plume.

1. Introduction

Controlling the processes of transfer of momentum, heat, and mass is an important fundamental problem in the mechanics of liquid, gas, and plasma. One of the modern and topical areas of this topic is the intensification of heat and mass transfer processes when the medium moves with the help of organized structures. Some researchers call this direction the structural approach. Known methods for assessing the interaction of a vortex formation with a flame front use the analysis of the characteristic hydrodynamic and chemical scales of the process. At present, much attention is paid to very large-scale motions or superstructures [1] with characteristic spatial scales of the order of $l/d \sim 20$. Such formations are recorded in various types of flows: in the boundary layer when flowing around a plate, as well as in pipes and channels. Large-scale motions are known in the mixing layer of jet streams [2], which are characterized by a ratio of $l/d \sim 10$-$16$. As shown by our studies [3], there is a class of jet flows, where superstructures are formed with a rather large size $l/d \sim 20$-$25$ and more. Such vortex scales can be observed in the case of jet outflow from long axisymmetric channels at low Reynolds numbers. Vortex structures flowing out of a long tube propagate downstream, forming superstructures disturbing the laminar flow.

The dynamic action on the front of a diffusion flame of objects of different scales, such as a single vortex or a packet of vortex structures as well as systems of laminar or turbulent jets can actively influence the completeness and stability of combustion, and in certain modes lead to flame blowout. One of the promising objects of research can be a method for controlling the combustion of a fuel jet based on the dynamic characteristics of a jet flowing out of a tube during the transition from a developed laminar Poiseuille flow to a turbulent flow.

The characteristic scales for the combustion of premixed mixtures are the thickness of the laminar flame and the speed of its propagation. An important characteristic of the mutual influence of the dynamics of flow and combustion is the flame stretch parameter $k = \frac{1}{\delta A} \frac{d\delta A}{dt}$. It is often assumed that large-scale eddies cause stretching of the flame front, and small-scale pulsations determine the
expansion of the flame preheating zone [4]. A significant number of practical burners operate in turbulent flow conditions. Under the influence of turbulent pulsations, the flame is deformed and stretched. In turn, changes in thermophysical properties as a result of heat release and composition affect the flow.

Turbulence is characterized by a cascade of scales, ranging from the characteristic dimensions of the channel up to the Kolmogorov scale of viscous dissipation. It is known that not all part of the turbulent spectrum is directly involved in the interaction with combustion.

In the scale range starting from the Gibson scale \( L_G = S_L'/\varepsilon \), where \( \varepsilon \) is the rate of dissipation of the kinetic energy of turbulence, and below up to the Kolmogorov scale, flow pulsations cannot lead to noticeable deformations of the flame. However, there are works [5] in which it is stated that the greatest stretch effect is achieved on the Kolmogorov scale. For the analysis of turbulent combustion, it is customary to use the turbulent Karlovitz number:

\[
Ka = \left( \frac{u'}{S_L} \right)^{1/2} \left( \frac{\delta_{th}}{L} \right)^{1/2} \quad \text{and the turbulent Damköhler number } \quad Da = L \cdot S_L' / (\delta_{th} u').
\]

For a mixed flame, only the time scale matters \( t_f \). A diffusion flame is characterized by two time scales: one characterizes the movement of the medium, and the other one \( t_C \) is "chemical time". In conditions of extinction, both of these scales are equal: \( Da = \frac{1}{\chi_S t_C} \). In the literature [6-12], various maps of the combustion modes of a homogeneous mixture are presented. They contain various models of action of vortex formation on combustion with the use of empirical data. For hydrocarbon fuels, such approaches usually allow one to obtain an adequate classification of flame - vortex interaction scenarios.

In contrast to the combustion of premixed mixtures for diffusion combustion, such important parameters as the propagation velocity of the laminar flame and the thickness of the flame \( u = \left( \frac{\lambda / C_P}{\rho v_k} \right)_{th} \) cannot be used to build evaluation criteria. Instead, a diffusion scale is introduced: \( l_{FD} = (D/k)^{1/2} \), where \( k \) is the strain rate due to the dynamics of the flow in the reacting flow. To analyze diffusive combustion [13, 14], the scalar dissipation rate \( \chi_s \) is used, but such criterion is very inconvenient for the analysis of experimental data. The flame will be locally quenched [14] when the flame/vortex interaction stretches the diffusion flame. Local extinction can lead to the formation of a line of discontinuity of the flame front and formation of a triple-flame structure along the flame rupture boundary. Due to high reaction rates and molecular diffusivity, \( \text{H}_2 - \text{air} \) mixtures are about 30 times stronger than \( \text{CH}_4 - \text{air} \) measured in terms of extinction strain rates. In this paper, we consider the features of the effect of vortex superstructures on an attached diffusion plume oriented vertically upward in still air.

2. Experimental procedure

The experimental setup consisted of gas cylinders, gas reducers, two flow meters, and a jet source. Gas consumption and fuel mixture composition were set using digital El-Flow Bronkhorst flow meters. Round tubes with an inner diameter \( d = 3-8 \text{ mm} \) and a length \( l / d = 200-300 \) were used as a jet source. Several experimental methods were used in the work: high-speed visualization and PIV with a video recording frequency of 7 kHz based on a Photron SA5 high-speed camera. The fuel flow, sown with light-scattering particles, was illuminated with a laser sheet. Both isothermal flows (CO2, propane) and diffusion flames (C3H8 or H2 mixed with CO2) were studied.
Figure 1. Superstructure in a laminar jet: changes in the axial velocity component on the axis of the CO\textsubscript{2} jet, PIV data, \( d = 8 \text{ mm} \).

The characteristic longitudinal and lateral scales of the event can be estimated from the data presented in Figure 1. Here, according to our estimates, \( l/d \approx 50 \). The nature of the change in the axial velocity has a form similar to the puff-type structure, characteristic of the process of laminar-turbulent transition in a long tube. First, there is a gradual deceleration of the flow, accompanied by an increase in the intensity of pulsations. The stream then returns to its original state in a very short period of time. The difference between a free jet and a flow in a pipe is, in particular, that the superstructure leads to a simultaneous loss of flow stability over the entire initial section of the jet.

Figure 2. Footage of the reaction of the attached C\textsubscript{3}H\textsubscript{8} flame when a vortex superstructure appears in the paraxial region.

In contrast to isothermal flow, the front of the diffusion attached flame localizes the propagation of vortex disturbance in the axial fuel region of the flame. According to our estimates made on the basis of high-speed visualization of a propane-air torch, the velocity of propagation of the disturbance along the axis during combustion increases by almost an order of magnitude compared to the isothermal case. Figure 2 shows high-speed rendering frames. The flow was sown with TiCl\textsubscript{4} vapor. Figure 5 shows the
frames of visualization of the reaction of the diffusion flame H2 / CO2 at the moment of the passage of the disturbance (frames 1-3). A short-term decrease in the length of the plume and the appearance of instability in the far flow field are visually observed. With a decrease in the proportion of hydrogen in the fuel mixture [15], the nature of the impact is closer to a corrugated flame and is accompanied by local zones of flame front extinction. Note that this character of the effect of dilution of the fuel with an inert gas (i.e., a decrease in SL) is in qualitative agreement with the premixed combustion regime diagram [11].

Conclusions
When superstructures interact with the flame front, the question of choosing the determining scales becomes ambiguous. Apparently, the features of the perturbation interaction can depend on the acoustic characteristics of the flows and, accordingly, on the nature of the density distribution in the plume. To analyze the adequacy of the combustion regime maps, complete information is required on the detailed three-dimensional structure of the vortex formation, including information on the kinetics of the chemical reaction.

Acknowledgments
This work was supported by the Ministry of Education and Science of the Russian Federation (No. AAAA-A17-117030310010-9) and RFBR (No. 17-08-00958).

References
[1] Schumacher J, Eckhardt B, Haller G 2017 Euromech colloquium 586: turbulent superstructures in closed and open flows
[2] Brown G L, Roshko A 2012 J. Turbulence 13(51)
[3] Lemanov V V, Lukashov V V, Abrakhmanov R Kh, Arbuzov V A, Dunishev Yu N, Sharov K A 2018 Combustion, explosion and shock waves 54(3)
[4] Doan N A K, Swaminathan N, Chakraborty N 2017 Proc. of Comb. Inst. 36
[5] Lipatnikov A N, Nishiki S, Hasegawa T 2014 Phys. Fluids 26(10) 105104
[6] Renard P-H, Thevenin D, Rolon J C, Candel S 2000 Progress in Energy and Combustion Science 26 225–82
[7] Barrere M 1974 Revue Generale de Thermique 148 295–308
[8] Bray K N C 1980 Turbulent flows with premixed reactants ed Libby P A, Williams F A Topics
in applied physics (New York: Springer) 44 115

[9] Borghi R 1985 On the structure and morphology of turbulent premixed flames ed Casci C, Bruno C Recent advances in the aerospace sciences (New York: Plenum Press) pp 117–38

[10] Williams F A 1985 Combustion theory. 2nd ed. Reading (MA: Addison-Wesley)

[11] Peters N 1986 21st Symposium (Int.) on Combustion 1231–50

[12] Bilger R W 1988 22nd Symposium (Int.) on Combustion (Seattle, WA, The Combustion Institute, Pittsburgh) pp 475–88

[13] Peters N 1991 Length scales in laminar and turbulent flames ed Oran E S, Boris J P (Numerical approaches to combustion modeling, Progress in astronautics and aeronautics, Washington, DC: AIAA) 135 pp 155–82

[14] Hermanns M, Vera M, Liñán A 2007 Combustion and Flame 149 32–48

[15] Dubnishchev Yu N, Arbuzov V A, Lukashov V V, Sharov K A and Lemanov V V 2019 Optoelectronics, Instrumentation and Data Processing 55 16–9