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Infrared thermographic evaluation of flame turbulence scale

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HIGHLIGHTS

- 2–16 Hz flame temperature pulsations are conditioned by flame flow parameters.
- Experimental temperature patterns correlate well with flame turbulence scale.
- Turbulence scale in a chemical gas can be evaluated by temperature variations spectra.
- The micro-volumetric burning in turbulent vortices is a determinative mechanism of fuel burning.

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ABSTRACT

This paper reports both theoretical predictions and experimental results of the use of infrared thermography for determining the scale of turbulent vortices in flames of burning liquid hydrocarbon fuels and flammable vegetation. The size of flames, as indicated by temperature instabilities observed in infrared thermograms, agrees fairly well with the size of turbulent vortices calculated by analyzing the spectra of flame temperature pulsations.

1. Introduction

Flames appear in many burning processes. Oxidation reactions in flames take place either due to the forced supply of an oxidant to the reaction zone or to oxygen diffusion from the environment. Depending on burning conditions, the gas flow in flames can be either laminar or turbulent. In the case of diffusive burning, flames are accompanied by considerable turbulence [1]. Flame fronts propagate with gases at different velocities and pulsation amplitudes that can each be characterized by both a mean value and a standard deviation. Therefore, a flame front exhibits a complex, unstable structure with an expanding volume. This increases the rate of reactions. Turbulent burning is a complex process. The combustion of the primary materials ignites other chemical constituents that would not burn by themselves. In these conditions, the laws of laminar flame propagation do not apply, and the flame pulsations influence the intensity of turbulence.

Depending on the magnitude of turbulent pulsations, one may consider a number of combustion mechanisms that might appear in turbulent flows [2].

If the extent of turbulence is small compared to the thickness of a laminar flame, and the pulsations of turbulence move more slowly than the laminar flame, the corresponding burning process is volumetric. The volumetric burning model is based on the assumption that a turbulent flame structure is close to that of a corresponding laminar flame [3]. Similarly, a turbulent flame consists of a warm-up zone and a region where volumetric chemical reactions take place. First of all, small-scale turbulence affects the heat and mass transfer in the flame. Thus, the theory of laminar flames is fully applicable to a volumetric model if molecular transfer coefficients are replaced by turbulent ones.

In situations where a turbulence scale exceeds a width of a reaction zone, Damkölhler proposed a flame model where a flat flame front is disturbed by becoming a tangle of laminar fronts [4].

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Nomenclature

Symbols

l	length, m
h	height, m
T	temperature, K
t	time, s
L	flame jet height, m
f	frequency, Hz
k	intermediary parameter, m^2/s^2
Tu	ratio between the kinetic energies of turbulence and averaged flow
b	turbulent vortex scale, m

Greek symbol

ρ	density, kg/m^3

Abbreviations

IR	infrared
HD	hydro-dynamical
T	thermo-physical
exp	experimental

In this regime, laminar flames separate into regions of unburned and fully burned materials. Such regions may proceed in the flow, being accompanied by intensive pulsations of both temperature and reactant concentration.

A fairly intensive turbulence can cause not only disturbance in a laminar flame front but also cause the flame front to split into separate regions [5]. Additionally, the burning occurs not in an extended region, similar to a laminar flame front, but in micro-zones that are distributed through a region of turbulent burning.

In this case, laminar, or micro-scale, flame fronts do not appear because there is not enough time for their formation on the boundaries between the quickly-moving regions of the raw combustion mixture and the burning products. According to Spalding's hypothesis [6], the burning takes place within many separate vortices. A feature of such model is that, because of dissipation, vortices split into consecutively smaller fractions. The interfaces between these fractions and the hot gas are large enough to support the burning process.

However, in spite of much research in this field [7–11], a scientific description of turbulent burning processes is challenging. The theoretical and experimental aspects of this problem are not yet fully explored and additional research is necessary. The authors believe that the burning processes in turbulent flames would be analyzed best by remote experimental methods, especially infrared (IR) thermography. In most earlier experimental work, numerous thermocouples were inserted into a flame. Unfortunately, the presence of the thermocouples may disturb the gas flow in the flames and thus may influence the burning process, and this could influence the test results and conclusions. With thermography, dynamic temperature distributions can be visualized without disturbing the flame [12–16]. If any thermocouples are used, the number of them would be greatly reduced. Earlier research has shown that the flame temperature fluctuates in time [12,15,17], and the corresponding temperature spectra are characterized by specific frequencies [12,17]. These flame frequencies within a flame are influenced by the movement of local temperature structures, which are related to the flow structure. These are called 'flame patterns' when observed by IR thermography.

The distributions of flow velocity, current-flow lines and temperature instabilities in hydrocarbon flames were discussed in [18–21]. It follows from the published results that flame temperature pulsations are closely related to turbulent flow regimes in flames. The contribution of flame turbulence to the propagation of a burning flame front has been analyzed using mathematical models similar to those that were used to describe the propagation of forest fires [22–27]. Some studies were devoted to the analysis of flame turbulence using the Planar Laser-Induced Fluorescence (PLIF) method, which allows the visualization of cross-sections of 3D physical phenomena, such as velocity, concentration, temperature and pressure [28–30].

The flame turbulence scale is considered to be an important parameter that strongly affects transfer coefficients [31] and the burning process as a whole, as shown by mathematical modeling [32–34]. The results of experiments on burning methane showed a relationship between the radiation of diffusive flames and turbulence characteristics [35]. Some results of numerical modeling of the 3D structure of turbulent flames were reported in one work [36]. Simulation has included both Large Eddy Simulations and Direct Numerical Simulations. And experimental methods have included both tomography and Particle Image Velocimetry (PIV). However, even if many characteristics of flames have been well documented by both experiments and simulation, the size of flame vortices has not yet been completely analyzed.

By using the methods mentioned above, it is interesting to determine the characteristic size of flame temperature patterns, as well as to evaluate their turbulence scale. In this paper, we present experimental results obtained by using IR thermography for the evaluation of both the flame temperature spectra and the size of flame temperature patterns. These results are compared to theoretical estimates of the turbulence scale in flames involving the burning of flammable vegetation and some liquid hydrocarbon fuels.

2. Experimental setup for the evaluation of flame temperature spectra

Fig. 1 represents the experimental setup where the sources of IR radiation (both the reference blackbody and flames to be analyzed) and the IR camera were placed along the same optical path.

A Russian-made blackbody source, AChT-45/100/1100, was used to provide reference temperatures from 573 K to 1773 K.

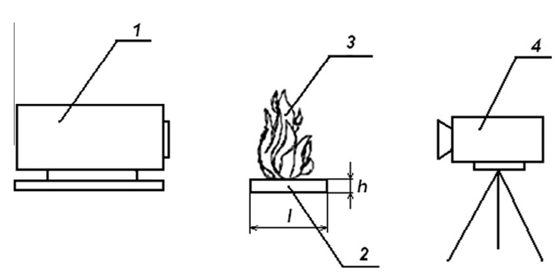

Fig. 1. Experimental setup for studying radiant properties of flames: 1 – blackbody reference AChT-45/100/1100, 2 – containers with FV (l – length, h – height), 3 – flame, 4 – IR camera (JADE J530SB).