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Stable vortex structures in axisymmetric convective torch during oscillating combustion

P. P. KHRAMTSOV, O. G. MARTYNENKO, V. S. BURAK and I. A. SHIKH
Luikov Heat and Mass Transfer Institute, Minsk, 220072, Belarus

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Abstract—A structure of a convective torch of axisymmetric flame in combustion of a propane–air mixture was studied experimentally under the conditions of velocity perturbations on the nozzle section. The flow was visualized by a Mach–Zehnder interferometer and also using stroboscopic photography of the flame proper luminescence. Mean temperature distribution in a torch was studied using a Chromel–Alumel thermocouple. The obtained data show the presence of torroidal coherent vortex structures moving downstream that substantially enhance combustion processes and heat transfer in a torch.

INTRODUCTION

At present of great interest to engineers and scientists are the physical processes occurring in oscillating combustion; that is stipulated by enhancement of torch heat transfer noted in a number of cases, by an increase in the velocity and completeness of fuel combustion and also by a decrease in the outflow of toxic radicals formed as a result of combustion. The process of oscillating combustion is experimentally observed in two main cases: first, this is a spontaneous origination of oscillations observed in singing flames or in self-oscillations of a torch during diffusion combustion; second, this is vibrational combustion caused by some engineering devices, such as acoustic emitter, periodically moving piston, gas valve modulating flow rate of fuel or oxidizer in time.

With all the variety of processes occurring in oscillating combustion the importance of some characteristics determining heat transfer should be emphasized, such as the structure of convective flow and temperature distribution in a torch. In an oscillating flame virtually all the parameters characterizing the process experience, to one degree or another, periodic variations, but in describing the mechanism of oscillating flow origination, depending on a specific situation, one or two parameters are taken as basic and the periodicity of the remaining parameters is considered as secondary.

Various approaches to the description of the mechanism of oscillating flame origination are presented in refs. [1, 2] in great detail. Of special interest are such processes of vibrational combustion when vortex structures, which exert a strong effect on both the process of combustion itself and the process of convective heat transfer of a torch, originate as a result of a periodic variation of velocity. In [3] experimental data obtained due to the study of the influence of acoustic oscillation on a flame are reviewed. However, by virtue of the fact that energy of sound oscillation is much smaller than the energy released during combustion, sound oscillations do not cause considerable changes in the flame structure except for the case when they distort its stability. Thus, in flames sensitive to sound oscillations an origination of vortexes is possible due to sound effect. A number of interesting changes in the flame shape that are observed under the effect of an intense sound on the combustion of a propane–air mixture issuing from a nozzle are explained by the fact that an outer flow past a burner does not leave the regime of a potential flow.

In vibrational flow in a tube pressure fluctuations may lead to a periodic change in the velocity of a fuel mixture supply to the combustion zone. In this case a change in the flow convective velocity of both a fuel mixture and combustion products may appear substantial due to an oscillating heat release that, in turn, leads to the formation of stable vortex structures in the combustion zone. In [4] the results of photography of the process of vibrational combustion of a fuel gas thin jet in a tube are presented. It is shown that in this case a chain of torroidal vortexes is formed on the flame outer surface. In the flame initial portion annular vortexes appear that then move jumpwise upward strictly with the period of acoustic oscillations. The authors pay attention to the fact that formation of vortexes during vibrational combustion leads to enhancement of the process from the view point of such parameters as increase of the completeness of combustion and heat transfer. In [5] the laws governing vibrational combustion originating in a tube during combustion of a pre-prepared fuel mixture are studied. The authors showed that in vibrational combustion of a propane–air mixture, a mean height of a flame increases with a frequency according to a

NOMENCLATURE

D	nozzle diameter [m]	$\langle T\rangle$	mean temperature of a torch [°C]
f	frequency of velocity perturbation [Hz]	z	coordinate along a torch [m].
l	distance between vortexes [m]		
r	coordinate across a torch [m]	Greek symbols	
V	velocity of a single vortex [m s^{-1}]	λ	wavelength of pulse lamp radiation [μm].
V_0	velocity on the nozzle section [m s^{-1}]		

hyperbolic law. The effect of flame oscillation on heat transfer of combustion products to tube walls was studied in [6]. It is shown that a heat flux on a tube wall directly behind the flame front with oscillations is much greater than in the case of motion of combustion products in the absence of oscillations. Apparently, the formation of vortexes is the main process affecting the height of a diffusion flame. In [4] an interferogram recorded on a Mach–Zehnder interferometer and confirming the presence of vortex structures in an oscillating diffusion flame is presented. In ref. [7] it is shown that considerable fluctuations of flow velocity over the height are presented in an oscillating diffusion flame and the calculation of a flame height is performed, the results of which are in good agreement with real photographic scanning of an oscillating combustion.

In the present paper the study of the structure of vortex formations originating in an axisymmetric flame during propane–air mixture combustion in the presence of periodic velocity perturbations on the nozzle section is performed. The flow was visualized by a Mach–Zehnder interferometer and also by photography of flame proper luminescence. In this case a technique of a stroboscopic photography was used due to a weak intensity of proper luminescence. The distribution of an averaged temperature of a torch was studied by a Chromel–Alumel thermocouple.

EXPERIMENTAL TECHNIQUES AND EQUIPMENT

In the present paper a flame of a propane–air mixture issuing from the round nozzle with a diameter 0.17 m was studied. A fuel mixture was fed to a cylindrical tank equipped with a magnetodynamic sound emitter. The ratio of a propane–air mixture was maintained equal to 1 : 6 during the entire experiment. As a result of a periodic motion of a magnetodynamic diffusor which in the given case operated as a piston performing slight motions relative to an equilibrium position, periodic fluctuations of a flow velocity of a fuel mixture originated on the nozzle section. A gas tank together with a nozzle represents a Helmholtz resonator. To prevent flame front propagation inside a tank and also to level the originating gas flow a metallic net was positioned in a nozzle. In the absence of perturbations the velocity on a nozzle section amounted to ~ 2 m s^{-1}.

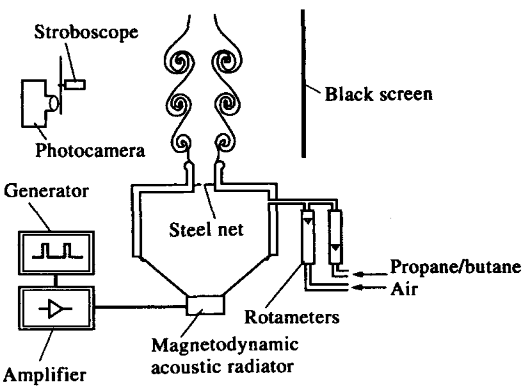

Fig. 1. Structural scheme of an experimental setup.

A scheme of an experimental setup is given in Fig. 1. Butane and air consumption were regulated by rotameters. Photography of a flame section was performed via a stroboscopic chopper of radiation, the frequency of whose interruption corresponded to the frequency of rectangular pulses with a duration 1 μs supplied through an amplifier of a sound frequency to a magnetodynamic emitter. A mean temperature of combustion products in a convective torch was regulated by scanning the flow region with a Chromel–Alumel thermocouple. To totally visualize the flow and to reveal specific features of a flame, temperature distribution interferograms of the bands of an infinite width were recorded by a Mach–Zehnder interferometer. A pulse lamp with the discharge energy 10^3 J served as a light source. An interference filter emitting radiation with a wavelength $\lambda = 0.543$ μm was positioned directly behind a lamp.

EXPERIMENTAL RESULTS AND DISCUSSION

The presence of velocity fluctuations on the nozzle section in the case of an axisymmetric free jet leads to the formation of a sequence of torroidal co-axial vortexes moving toward a main flow [8]. In this case, depending on the amplitude, velocity and frequency of these vortexes passing, either a rather vivid transformation of a jet to a sequence of non-interacting vortexes or a complex picture of a flow originating as a result of non-linear interaction of vortex structures with each other and with a velocity field of a jet turbulent flow may be observed. This situation is realized when the distance between the centers of the nearest vortexes becomes smaller than some minimal comparable, as a rule, with a scale of a single vortex [9]. Figures 2 (a)–(d) present the results of stroboscopic photography of flame luminescence and the interferograms for the cases of flow velocity perturbation

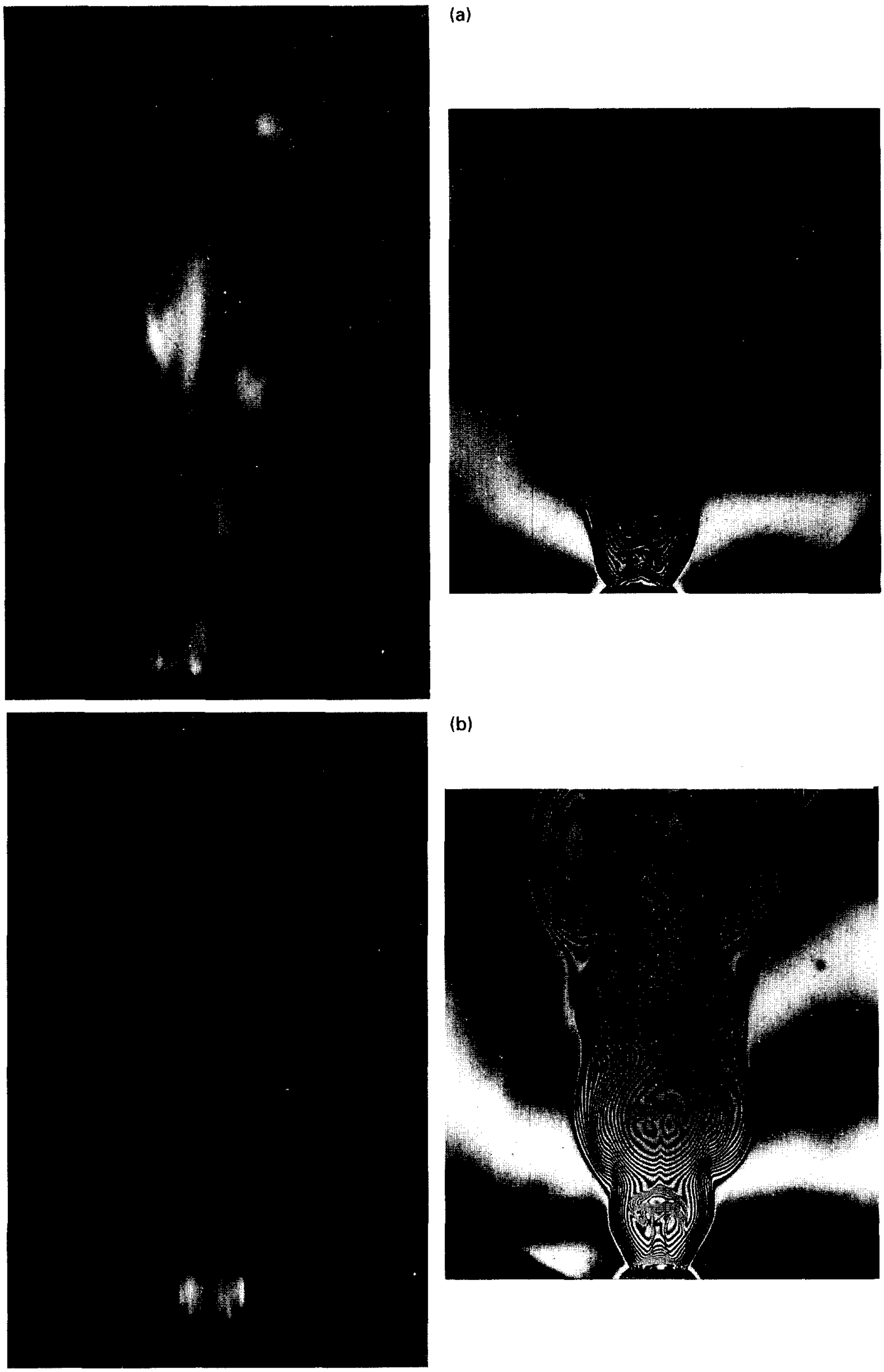

Fig. 2. Stroboscopic photograph and the interferogram of a convective torch in oscillating combustion: (a) $f = 50$; (b) 75; (c) 100; (d) 150 and (e) 200 Hz.

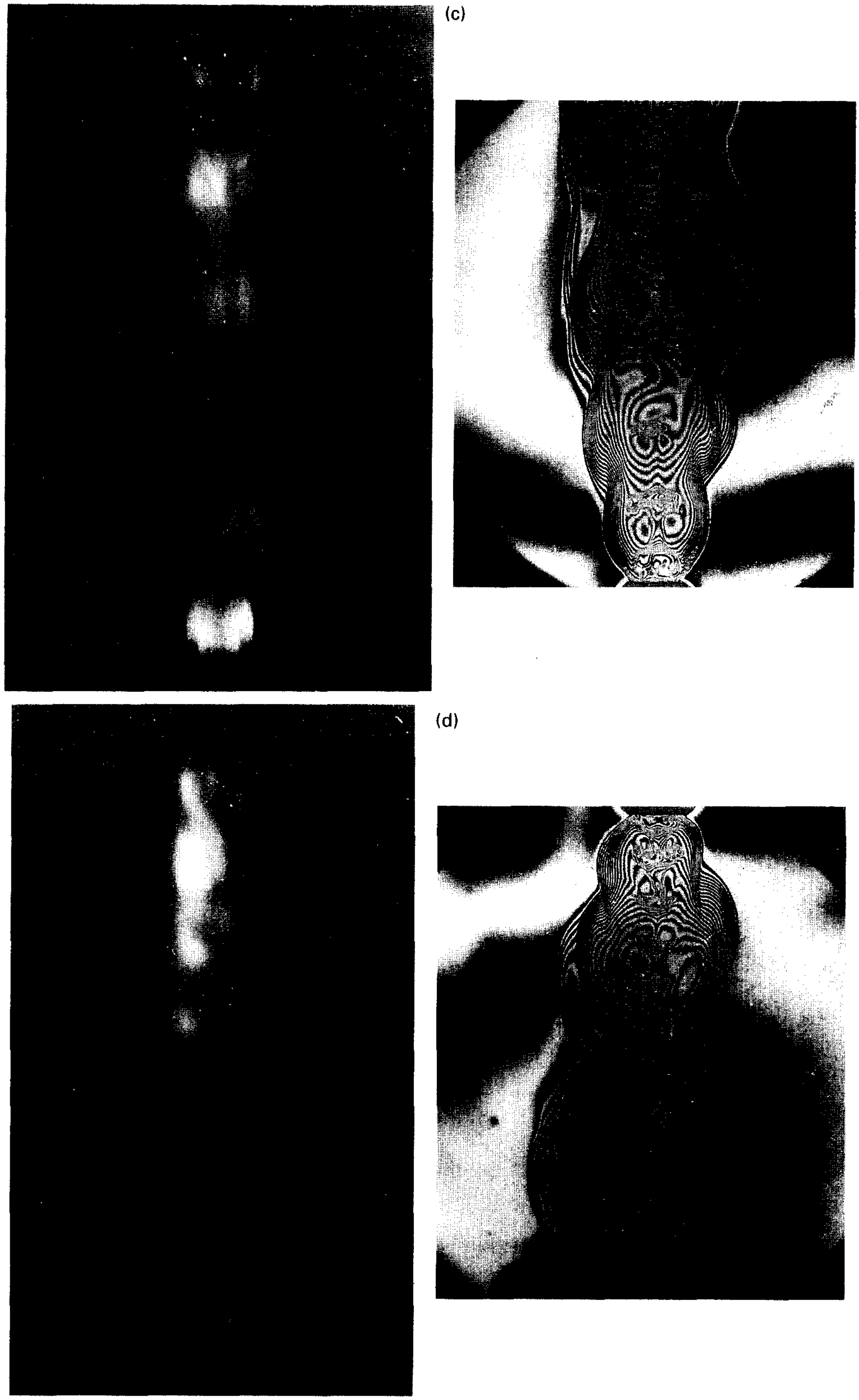

Fig. 2—*continued.*

(e)

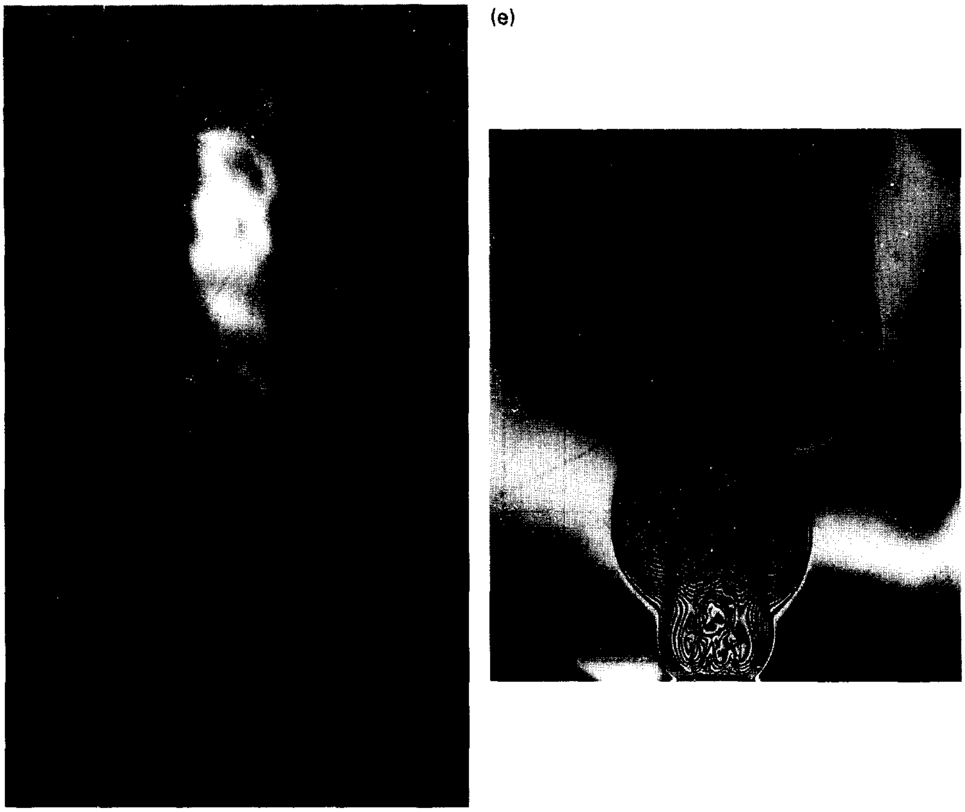

Fig. 2—*continued.*

of a fuel mixture on the nozzle section with frequencies within the region $f = 50$–200 Hz. As well seen from the presented photographs, a gas flow in a flame is structured in a series of sequential toroidal vortexes moving one behind the other. In this case a flame front experiences periodic interruptions along a torch, probably attributed to a vortex gas flow. Because the frequency of the pulses of velocity perturbation of a fuel mixture on the nozzle section is the only parameter changing during the experiments, the data obtained as a result of photography may be used to determine the dependence of the distance between the vortexes and the velocity of their motion on the frequency of perturbations.

Figure 3 presents the graph of the dependence of the distance between the vortexes on the frequency of the repetition of disturbing pulses. As is seen from the figure the distance between the nearest vortexes decreases rather quickly with the frequency according to the hyperbolic law. In Fig. 3(b) the graph of the dependence of the velocity of motion of vortexes on the frequency of perturbations is shown that indicates that in the studied range of the variation of regime parameters this dependence is virtually linear. It is interesting to note that starting from the frequency $f = 100$ Hz and above, the distance between some vortexes becomes smaller than the characteristic scale of the vortex itself, however no traces of the interaction of vortexes are observed. In the absence of combustion the vortexes with such a small distance between them should interact rather strongly [9]. This fact can be, apparently, explained by the following: in the studied case the motion of a vortex is stipulated by two factors, first, the vortex moves due to the velocity induced by a circulating gas flow inside a vortex, second, the vortex motion is also initiated by a buoyancy force causing a convective gas flow.

Figure 4 presents the results of radial scanning of a flame by a Chromel–Alumel thermocouple at a distance from the nozzle section equal to $3D$. As is seen from the graph, in the case of the absence of perturbation a vividly manifested drop of the mean temperature is observed in the torch center. At the frequency of disturbing pulses $f = 50$ Hz the drop becomes much smaller and at higher frequencies it vanishes virtually completely. This temperature distribution is caused by intense convective heat exchange between the torch center and its periphery zones as a result of vortical motion. Under these conditions completeness of propane–butane combustion and consequently thermal efficiency of the combustion process turn to be much higher compared to combustion in the absence of perturbations. The results of torch longitudinal scanning by a thermocouple, presented in Fig. 5, show that the velocity of the growth of a mean temperature downstream is much greater in the presence of initial perturbations of the flow velocity of a fuel mixture on the nozzle section than in their absence. A mean temperature attains its maximum value on the plateau at a distance of about

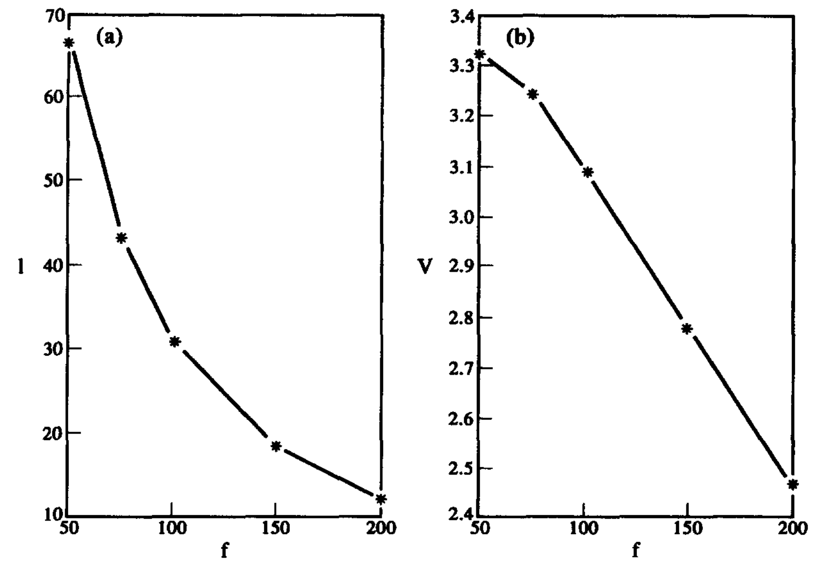

Fig. 3. Dependence of the distance between two nearest vortexes (a) and the velocity of the motion of vortexes (b) on the frequency of periodic perturbations of flow velocity of a fuel mixture.

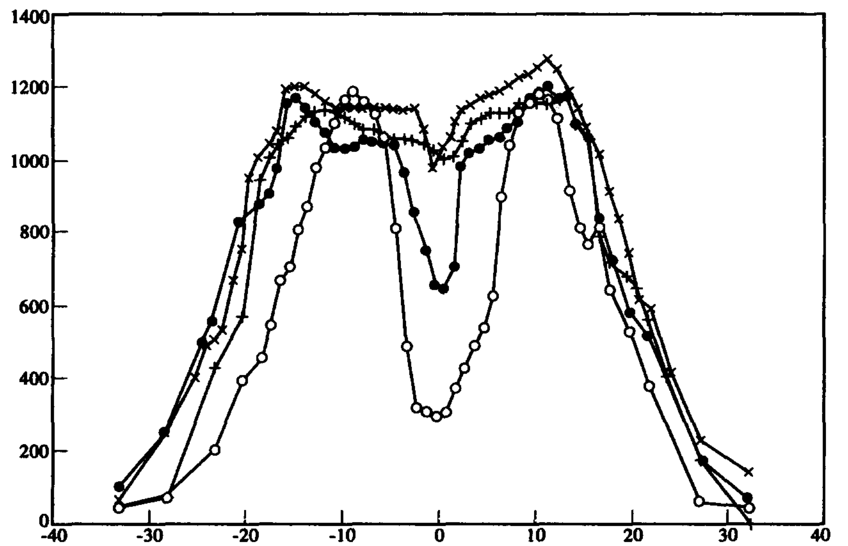

Fig. 4. Transverse distribution of a mean temperature in a torch at different frequencies of periodic perturbations of velocity and without perturbations: (○) $f = 0$; (●) 50; (+) 75; (×) 100 Hz.

$3D$ from the nozzle section, whereas in the absence of initial perturbations of the velocity on the section a maximum temperature is attained at distances greater than $10D$, then a sharp drop takes place.

The presented data indicate a considerable enhancement of combustion rate and increase of the completeness of fuel combustion in the presence of periodic perturbations of the mixture initial velocity compared to ordinary combustion, because the consumption of fuel and oxidizer was maintained constant during the whole experiment.

CONCLUSIONS

Within the studied range of regime parameters in a convective torch formed in combustion of the air–propane mixture, butane periodic oscillations of the velocity of a fuel mixture on the nozzle section cause the generation of successive torroidal vortexes. It should be noted that the presence of vortexes in a torch essentially affects the flame structure: the flame as a whole becomes more stable and shortened due to more intense fuel burn-out and the flame front experiences periodic turbulences moving downstream synchronously with vortexes. The presence of vortexes leads also to a considerable enhancement of flame heat transfer. Radial distribution of a mean temperature is more uniform than in the absence of periodic perturbations of a fuel mixture when a typical temperature profile drop is observed in the torch center. The absence of a drop during a vortical flow in a torch is connected with the displacement of the reaction

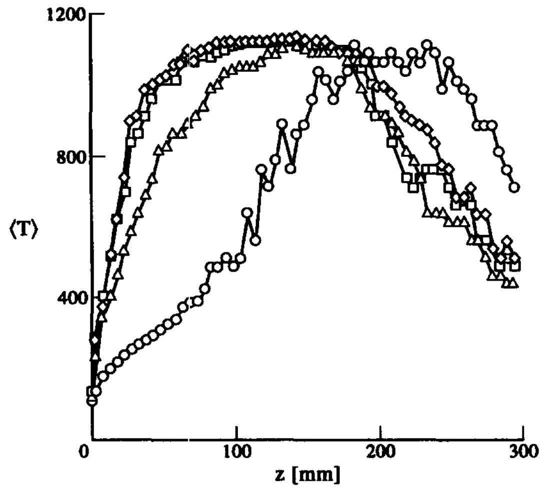

Fig. 5. Longitudinal distribution of a mean temperature in a convective torch: (○) $f = 0$; (△) 50; (□) 75; (◇) 100 Hz.

zone to the central region due to intense convective heat and mass transfer between the torch center and its periphery regions that is caused by circulating flows. An increase in thermal efficiency of the combustion process under the conditions of generation of vortexes, as judged by the value of the radial integral of a mean temperature in a torch, as well as substantial decrease of the zone of diffusion reburn indicate the growth of the completeness of fuel combustion under the present conditions.

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