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2D Simulation of Micro-Jet Excitation by Heat Source

Aleksandr A. Firsov[1]

Excitation of a laminar gas micro-jet by acoustic impact and by pulse-periodic heat source was simulated using the FlowVision software package in 2D formulation at normal conditions. Heat source imitates an electrical discharge. Air jet was formed by channel with inner size of 0.7 mm with the Poiseuille velocity profile at inlet boundary, the maximum profile velocity was varied in a range of 2.5–10 m/s. Influence of heat source frequency and power on the large-scale vortex formation was described. In the case of a jet with a speed of 5 m/s, the natural oscillations of the jet in response to a single pulse had a frequency f_{res} = 1380 Hz, so excitation of the jet was possible at close frequencies of 1190 Hz and 1500 Hz. At the same time, at a frequency of 1000 Hz (approximately equal to 2/3 f_{res}), every second impulse acted in antiphase and the oscillations developed poorly. Dependence of flow structure from the jet velocity was obtained. The results obtained show the possibility of exciting a micro-jet using low-power electrical discharges such as spark, DBD or corona.

Keywords: micro-jet, excitation, discharge, instability, modelling.

Introduction

Studies of the stability of jet flows and the mechanisms of their excitation are of significant interest for various devices, including burners and combustion chambers of various types, chemical reactors, and medical devices [1]. For example, work [2] provides data on the possibility of reducing NOx concentration during the combustion of a hydrogen jet in the air under acoustic influence. A significant part of work is devoted to the so-called micro-jets with a diameter of no more than 1 mm, which will be discussed in this work. The flow in micro-jets differs significantly from macrojets, the conditions for vortex formation change, and the penetration depth increases [3].

The closer the velocity profile is to parabolic (to the Poiseuille profile), the farther from the nozzle the laminar-turbulent transition and/or the excitation of instabilities of various types occurs. The velocity profile approaches parabolic due to the growth of the boundary layer, therefore, to obtain extended laminar jets, it is necessary to use long channels for which the diameter d is much less than the length L ($L/d > 100$). In the applied sense, it is interesting both to increase the stability of such jets and to the early excitation of instabilities, leading to intensified mixing of the jet with the surrounding moving or stationary gas and intensification of combustion [4, 5].

The classical method of jet excitation is to use acoustic vibrations [6], however, in most works, the use of a plane wave is discussed, i.e. non-local influence [7–9]. Electrical discharges of various types can provide local effects: form shock waves, be a source of volumetric force and heat generation. For example, spark discharges have been considered in various settings as an actuator that intensifies the mixing of a transverse gas jet with a supersonic air flow, both experimentally [10] and using numerical modeling [11, 12]. It is noteworthy that the stability of micro-jets and the possibility of their excitation using acoustic vibrations through numerical modeling were practically not considered, with rare exceptions [13]. Therefore, it seems interesting to consider, using numerical modeling, the stability of the microjets and the possibility of its local excitation using a pulse-periodic energy input simulating a discharge.

[1]Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Moscow, Russia

The article is organized as follows. Section 1 is devoted to description of a simulation model and boundary conditions. In section 2 we perform test of the ability to simulate the influence of an acoustic wave on a jet using FlowVision. Section 3 represents the results of simulation for fixed jet velocity at varying the frequency of the discharge and section 4 demonstrates the results for varying velocity of a discharge. Conclusion summarizes the study and reveals the possibility of using low-power electrical discharges such as spark, DBD or corona for exciting of a micro-jet.

1. Model and Boundary Conditions

Obtaining detailed data on the distribution of gas-dynamic quantities is extremely difficult in an experiment on excitation of a laminar micro-jet using an electric discharge. Numerical modeling can be used to obtain information about pressure and velocity fields throughout the entire study area. However, modeling has its limitations, for example, a three-dimensional problem has a significant dimension, i.e. solving such a problem requires either a large amount of computational time (weeks on available resources for each computational case), or a powerful computing cluster, but our group has limited access to such infrastructure. Therefore, a basic understanding of the influence of a weak disturbance created by an electric discharge on a laminar micro-jet was obtained in a 2D formulation.

Numerical modeling of the excitation of a jet by a thermal source simulating the operation of a discharge was performed using FlowVision 3.12 software package on a computer station with an Intel 4930K processor (6 cores) and 32 GB of RAM. The simulation is based on solving a three-dimensional non-stationary system of Navier–Stokes equations, but in one of the directions (z) the dimension of the problem was 1 cell. The turbulence model was disabled.

The calculation area is a rectangle with a length (along the stream) of 60 mm and a width of 50 mm and presented in Fig. 1. There is a tube located along the axis of symmetry on one of the walls. Considering the 2D setting, this is a flat canal 5 mm long with an internal dimension of 0.7 mm and an external dimension of 0.9 mm. On the edge of the tube, there is a square with a side of 0.1 mm, inside of which there is a "heat source" modifier, simulating the operation of a discharge. The project used a rectangular computational mesh with adaptation – an increased level of adaptation (refinement of the computational mesh) was used in the area of jet flow. Thus, there are 96 cells per length and 50 cells per channel thickness inside the tube, and the total number of cells in the project did not exceed 0.5 million.

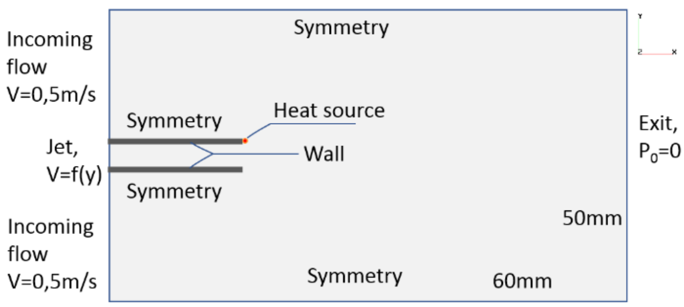

Figure 1. Calculation domain and boundary conditions

The "wall" boundary condition (no-slip boundary) was used on the inner wall of the tube and on the edge; a Poiseuille velocity profile was installed at the entrance of the tube; the maximum profile speed U_0 varied in the calculations and was set to 2.5, 5 and 10 m/s. At the entrance to the computational domain from the side of the tube, a constant velocity boundary condition of 0.5 m/s was set to minimize the mutual influence of pulsations created by the discharge. The working gas was air. Thus, the formulation of the problem is close to that described in [14, 15] for the case when the jet speed is greater than the oncoming flow speed. Therefore, the simulation results obtained for cases without discharge activation are close to the published experimental visualization. In part of the calculations, to accurately determine the concentration ratio between the jet gas and the associated gas and for better visualization, two gases were used: both having the properties of air. This made it possible to obtain visualization in the calculations similar to visualization using smoke/spray in the experiment. On the outer walls of the tube, as well as along the long boundary of the computational domain, a symmetry condition was established (a wall with slipping or a zero gradient of parameters). At the remaining boundary opposite the tube, a constant total relative pressure condition of zero was established. The relative temperature at all permeable boundaries was zero. The reference temperature and pressure were set to 273 K and 101000 Pa, respectively.

2. Testing the Ability to Simulate the Influence of an Acoustic Wave on a Jet Using FlowVision

To determine the possibility of modeling the influence of small pressure disturbances on the jet, a calculation was made of the acoustic excitation of a laminar jet with a speed of $U_0 = 6$ m/s in the absence of a cocurrent flow. For this purpose, the lower and upper boundaries of the computational domain were changed from symmetry to the variable pressure domain (plane wave – sinusoidal disturbance with an amplitude of 2 Pa and a frequency of 1000 Hz) and to the non-reflective Riemann condition, respectively. In the absence of artificial pressure disturbances, the jet was deformed at a distance of more than 10 jet calibers, which is clearly visible both from the gas velocity distribution and from the pressure pulsations shown in Fig. 2. The inclusion of a source of variable pressure at the boundary of the computational domain led to the creation of a variable pressure gradient in the region of the edge of the tube, and to the development of acoustic instability of the jet, which is visible both in the velocity distribution and in the form of small-scale pressure pulsations developing from the edge of the tube along the jet. Thus, modeling the excitation of a micro-jet using small perturbations can be simulated using FlowVision CFD. Therefore, we can move on to the next part of the work – modeling excitation using a pulse-periodic heat source simulating a discharge.

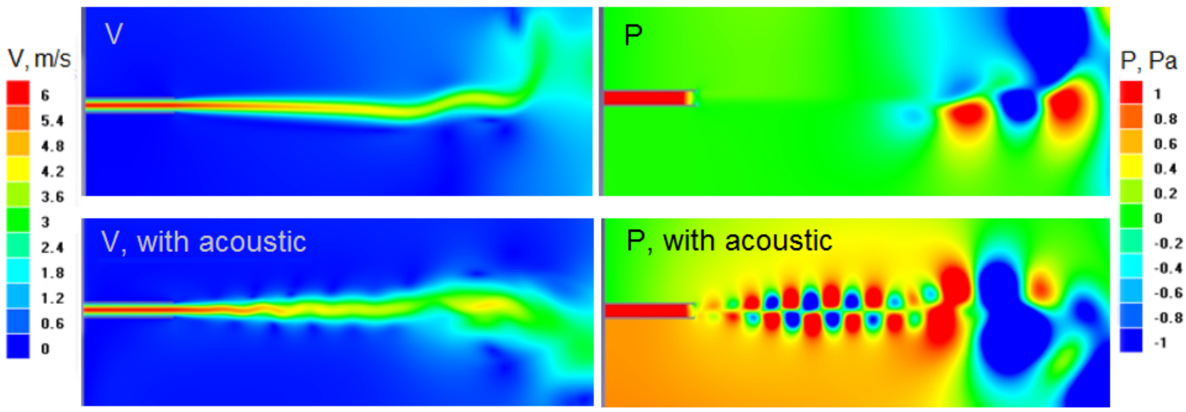

Figure 2. Velocity and pressure without and with acoustic excitation

3. Results for Fixed Jet Velocity at Varying the Frequency of the Discharge

The discharge was simulated by a volumetric heat source located on the edge of the tube in a square of 0.1 mm in size. The discharge heated a small volume of gas to the maximum relative temperature of 200–600 K. The discharge power at the time of operation was 0.005–0.012 W. During a series of tests of various energy input profiles, it was found that the most accentuated pressure pulse occurs when the heat source is instantly turned on/off. Thus, Fig. 3 shows a graph of the relative temperature in the discharge area with a heating power of 0.006 W, operating for 0.5 ms with a period of 1 ms (f = 1000 Hz) at a jet speed of 5 m/s. Turning on (and off) the heat source leads to pressure pulses in the near zone (i.e. in the area of the heat source), which are practically not felt at a distance from the source (in the far zone, 9 mm from the edge of the nozzle along the jet). However, as it can be seen in Fig. 3, in the jet region, these pressure pulses lead to the development and maintenance of pressure oscillations close to sinusoidal.

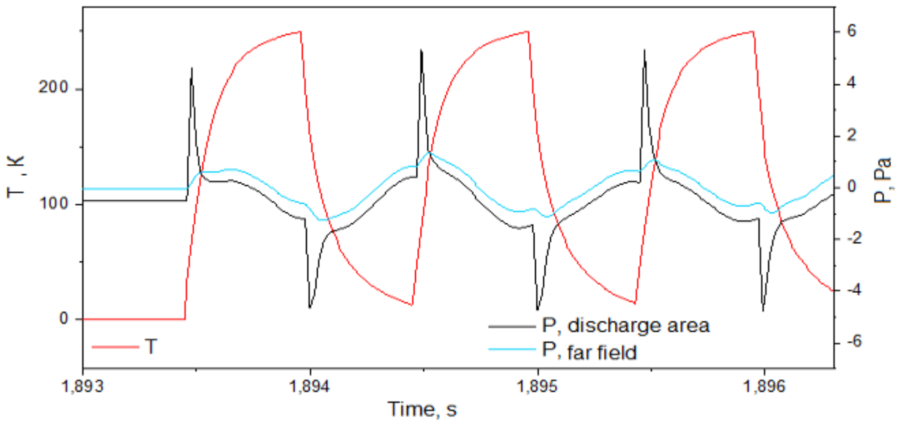

Figure 3. Time dependences of temperature and pressure caused by pulse-periodic heat source operation at f = 1000 Hz

The pulse repetition rate was varied at a jet speed of 5 m/s. Frequencies of 500, 1000, 1190 and 1500 Hz were considered, the spectra of the resulting pressure pulsations are shown in Fig. 4. Thus, at a frequency of introduced disturbances of 500 Hz, pressure oscillations occurred with a frequency of 1500 Hz (see Fig. 4) – the second pressure pulse, corresponding to turning off the heat source, was in phase with the oscillations initiated by the first pulse, corresponding to turning on. As a result, this mode of operation led to the development and maintenance of jet oscillations. At a frequency of introduced disturbances of 1000 Hz, the second pressure pulse, on the contrary, was in antiphase to the initiated oscillations, which greatly affected the resulting spectrum of pressure oscillations (see Fig. 4). When pulsations were introduced at frequencies of 1190 and 1500 Hz, pressure oscillations occurred at the same frequencies. The simulation results for the case of excitation of a jet by a discharge with a frequency of 1500 Hz are presented in Fig. 5. It can be seen that in the absence of a discharge, the jet's own instability is observed at a considerable distance from the tube, and the inclusion of a discharge introduces disturbances in the zone closest to the tube. It is important to note that the frequency of pressure oscillations resulting from the response to a single pulse (switching on and keeping the heat source switched on) was 1380 Hz.

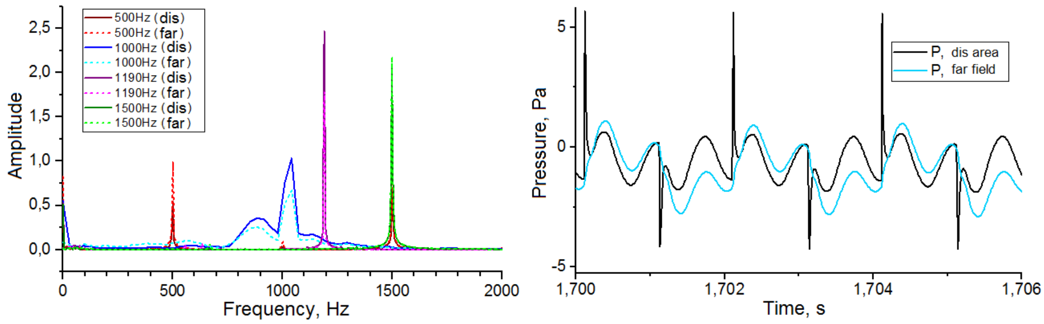

Figure 4. Spectra of pressure fluctuations in the jet with varying frequency of exposure and Pressure pulsations caused by a periodic heat source with a frequency of 1500 Hz

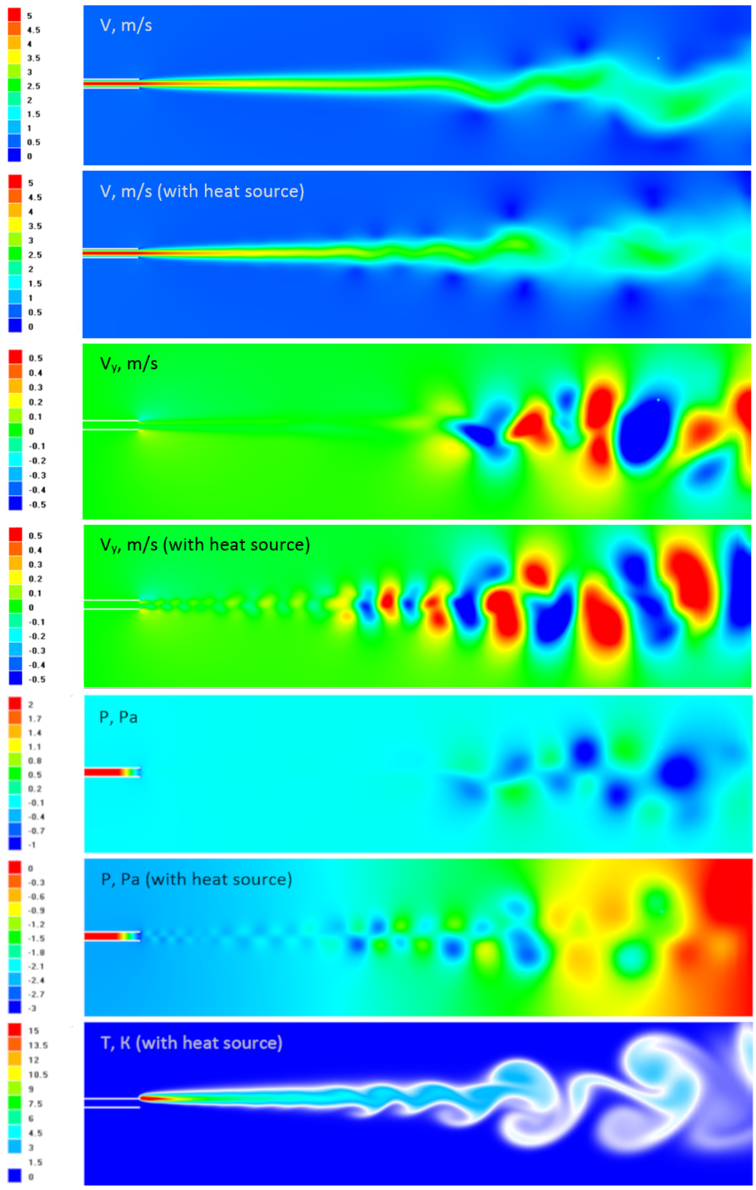

Figure 5. Results of simulation of jet instability at velocity $V = 5$ m/s for case without and with excitation of a jet by a heat source with a frequency of 1500 Hz

4. Results for Varying Velocity of the Discharge

The velocity of the gas jet was varied, and for ease of visualization, the calculation was carried out using two identical gases (both with the properties of air). Velocities of 2.5, 5 and 10 m/s were considered. At a speed of 5 m/s, the jet, as mentioned earlier, has its own velocity pulsations at a considerable distance from the tube, which are clearly visualized using the mass fraction of the jet substance, similar to visualization in the experiment. Turning on the discharge (frequency 500 Hz) led to the development of jet instability starting from the edge of the tube. The gas in the discharge area was heated by +250 K, an increase in the energy input into the discharge, such that the maximum heating relative to the reference data was +640 K, briefly led to a change in the flow structure, but after a short time (70 ms) the flow pattern became close to that obtained with a lower energy input. Visualization of the jet flow and a typical instability pattern at 5 m/s are shown in Fig. 6.

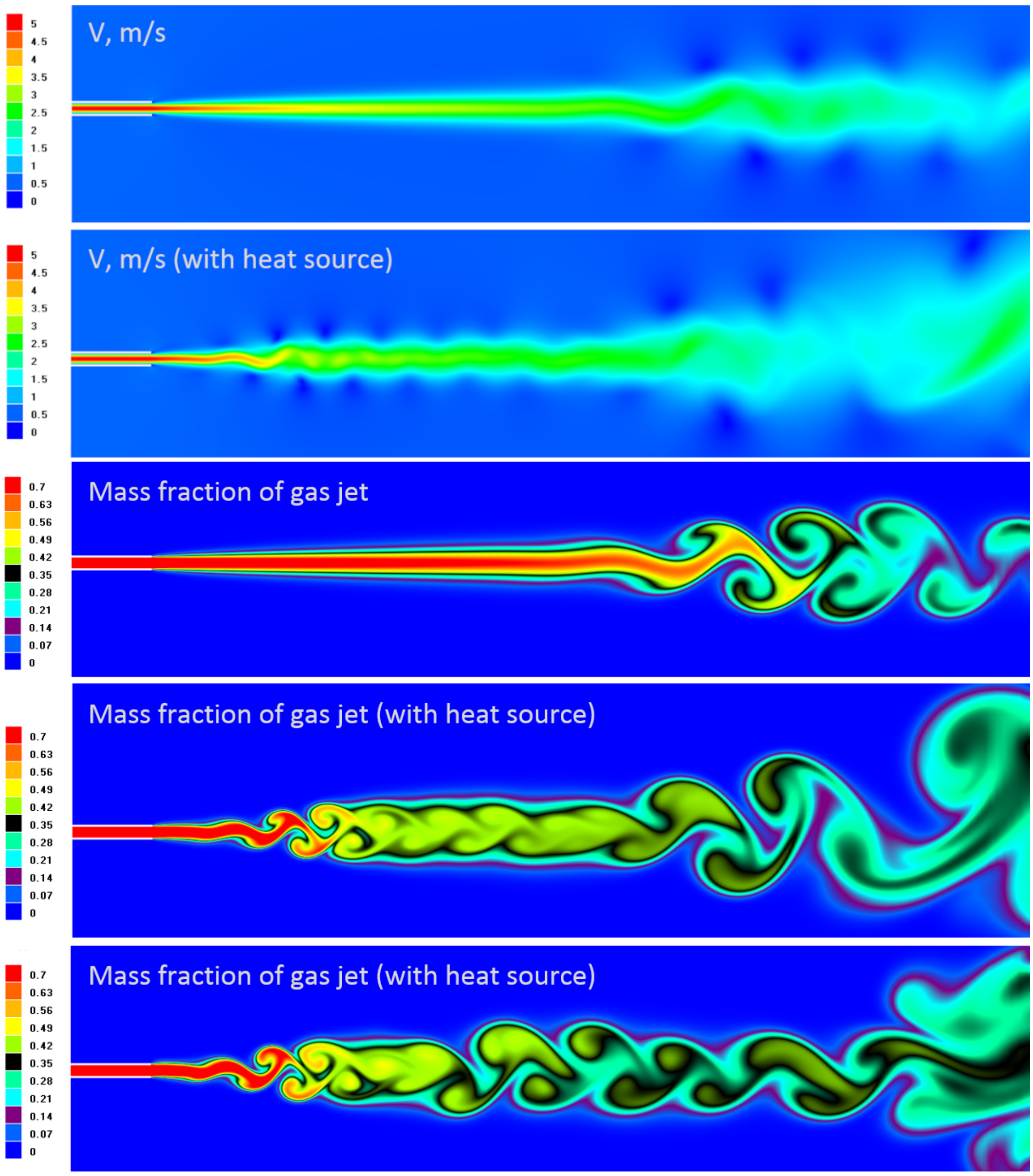

Figure 6. Results of simulation of jet instability at velocity $V = 5$ m/s for case without and with excitation of a jet by a heat source with a frequency of 500 Hz. Bottom image shows a temporary change in the flow structure caused by an increase in energy input

Reducing the jet speed to 2.5 m/s leads to stabilization of the jet flow and the absence of its own instability at a distance limited by the computational area. The inclusion of a pulse-periodic heat source leads to the appearance of pressure pulsations and a slight distortion of the jet shape, which increases with increasing energy input into the discharge, described for 5 m/s. The simulation results for a 2.5 m/s jet are presented in Fig. 7.

A jet with a speed of 10 m/s is extremely unstable; significant pulsations of speed, pressure and distortion of the shape of the jet are observed already at a distance of about 10 mm from the tube. Turning on the discharge leads to significant pulsations starting from the very edge of the tube, as shown in Fig. 8.

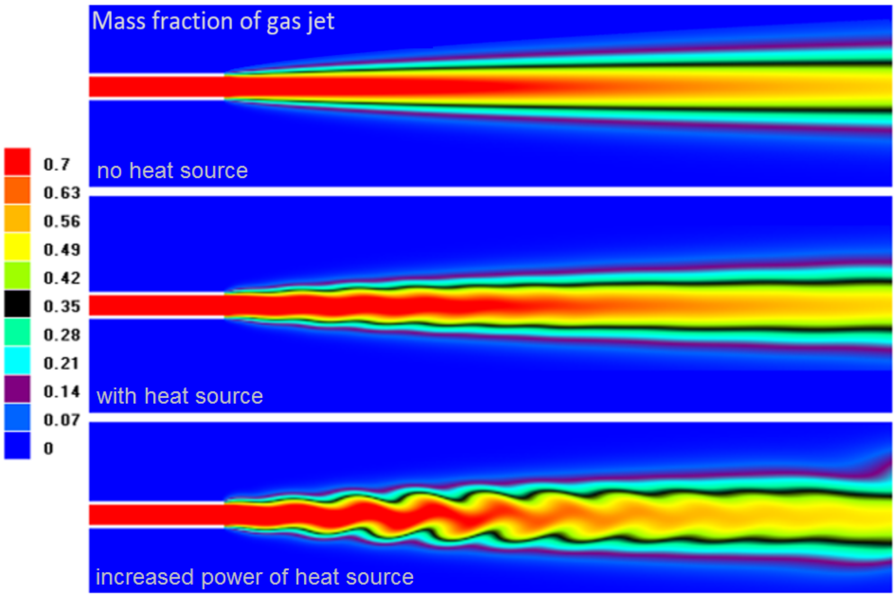

Figure 7. Visualization of a jet without a discharge, with a discharge (heat source) and with increased energy input. Results of simulation at velocity $V = 2.5$ m/s

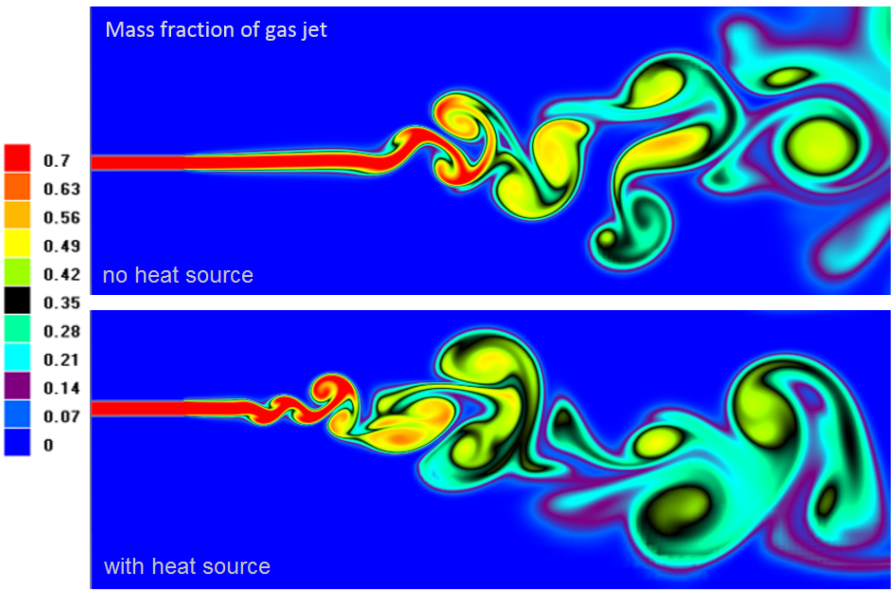

Figure 8. Visualization of a jet without a discharge and with a discharge simulated by heat source. Results of simulation at velocity $V = 10$ m/s

Conclusion

The acoustic and pulse-periodic heat source excitation of a laminar gas micro-jet is simulated using the FlowVision software package. Using numerical modeling, it is shown that in a two-dimensional formulation with a jet width of 0.7 mm and velocities of 2.5, 5 and 10 m/s, it is possible to excite jet oscillations using a pulse-periodic heat source with a power of a unit of milliwatts (5–12 mW). In the case of a jet with a speed of 5 m/s, the natural oscillations of the jet in response to a single pulse had a frequency $f_{res} = 1380$ Hz, so excitation of the jet was possible at close frequencies of 1190 Hz and 1500 Hz. At the same time, at a frequency of 1000 Hz (approximately equal to 2/3 f_{res}), the second pulse caused by turning off the heat source acted in antiphase with the pressure oscillations excited by the first pulse from turning on the heat source, and at this frequency the oscillations were initiated worse. At the same time, at a heat source frequency of 500 Hz (approximately equal to 1/3 f_{res}), the second pulse caused by turning off the heat source acted in phase with pressure oscillations excited by the first pulse from turning on the heat source, as a result of which the oscillations were excited no worse than at the main frequency of 1500 Hz. Dependence of flow structure from the jet velocity was obtained. It was shown that increase of jet velocity results in increase of natural oscillations and also disturbances of the jet excited by heat source. In all cases, at the heat source operation the jet oscillation zone moves closer to the tube. The results obtained show the possibility of exciting a micro-jet using low-power electrical discharges such as spark, DBD or corona.

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