The sudden outburst of hydrogen from a high-pressure reservoir into the atmosphere is accompanied by the formation of a supersonic jet. The temperature of hydrogen decreases as the jet expands, but there are factors that lead to a sharp local temperature increase due to conversion of the mechanical energy of the jet into thermal energy upon heating of the surrounding atmosphere in the starting shock wave and upon mixing of the hot air with the effluent fuel gas on a turbulized contact surface. The results of our preliminary numerical simulations of the self-ignition of hydrogen emitted into air upon sudden opening of a high-pressure vessel showed that, at an initial pressure of 150–400 bar and a nozzle output diameter greater than 2.6 mm, the intensity of a shock wave formed in air is sufficient to produce self-ignition of the hydrogen–air mixture formed behind the front of the propagating jet [1]. At an output diameter smaller than 2.6 mm, the ignition either does not take place or (even if it does) is rapidly quenched [2–4]. This behavior is caused by a decrease (related to a small outlet diameter) in the lifetime of zones where the temperature exceeds that necessary for the self-ignition of hydrogen–air mixtures. Owing to a self-similar character of the process, the shock-wave intensity drops with the distance from a small nozzle faster than in the case of a greater one.

The necessary safe outflow rate of emitted hydrogen can be provided using a perforated multinozzle unit with output diameters sufficiently small to ensure that the period of time during which the fuel gas is mixed with hot air is shorter than the self-ignition induction time [5]. However, if the nozzles are situated too close to each other, the adjacent starting shock waves can exhibit interaction [6, 7] leading to an additional increase in the temperature of the hydrogen–air mixture and, hence, to the risk of self-ignition.

The aim of this study was to elucidate the influence of the distance between nozzles on the possibility of self-ignition of a composite hydrogen jet emitted into air via a multinozzle array. The structure of a pulsed composite jet was experimentally studied for the efflux of nitrogen.

The interaction of pulsed jets was studied using a square (40 × 40 mm) shock tube connected to a vacuum (low-pressure) chamber and a high-pressure chamber. Replaceable two-nozzle units were mounted at the tube edge. The efflux took place after the reflection of a shock wave from the edge. All the nozzle units were sonic, with the critical cross-sectional diameters of both nozzles in the unit selected so as to ensure the total flow rate equal to that for a single nozzle with a critical cross section of 2.75 mm. The relative spacing defined as the ratio of the distance between the axes of nozzles to the critical diameter was \( l = 2.5, 4.4, \) and \( 6.2 \) (units I, II, and III, respectively). The low- and high-pressure chambers were filled with nitrogen at pressures within \( p_0 = 30–380 \) Torr and a temperature of \( T_0 = 300 \) K. The pushing gas was nitrogen (\( N_2 \)), helium (He), or a He–\( N_2 \) mixture. In this series of experiments, the ratio of the pressure \( p \) behind the reflected shock wave in front of the nozzle input to the initial value in the high-pressure chamber was \( n = p/p_0 = 45 \) and the Mach number at the nozzle output was \( M = 1 \). A series of schlieren photographs showing the composite flow formation from nonstationary jets was obtained for two-nozzle units with variable relative spacing of nozzles.

Figure 1 presents the pattern of nitrogen jets and overriding shock waves in air in the axial plane of a two-nozzle unit. An analysis of the photographs reveals three sequential stages in the formation of a quasi-stationary jet behind a multinozzle unit. The first stage begins upon the appearance of the effluent gas behind
the nozzle output, is accompanied by the formation of a characteristic wave structure, and terminates with the onset of interaction of the primary shock waves ($t = 11$ $\mu$s in Fig. 1). At this stage of the independent development of jets from each nozzle, the laws of motion of the wave structure are not influenced by the nozzle spacing. The duration of this stage depends on the nozzle spacing and changes from $4$ $\mu$s for unit I to $11$ $\mu$s for unit III.

In the initial stage of flow development, the pulsed jet from each nozzle propagates independently and is characterized by the formation of a starting shock wave, a contact surface with the vortex ring, and a secondary shock wave. In the second stage, the shock waves and vortices interact and eventually the resultant primary shock and the total vortices for both nozzles are formed ($t = 29$ $\mu$s in Fig. 1).

In order to determine conditions at which no diffusive self-ignition takes place in block jets, we have performed three-dimensional (3D) numerical modeling of the efflux of a hydrogen jet from a single nozzle and from an array of nozzles with the same total area. The simulation was based on a physicochemical model involving the gasdynamic transport of a viscous gas, the kinetics of hydrogen oxidation, the multicomponent diffusion, and heat exchange and involved the solution of the complete system of Navier–Stokes equations for the multicomponent gas mixture. The mechanism of the chemical kinetics of hydrogen oxidation was based on the Bowman–Miller scheme involving 11 components ($H_2O$, $O_2$, $H_2$, $OH$, $H$, $HO_2$, $N_2O_2$, $N_2$, $N$, $NO$) and the following 21 reactions:

1. $H_2O + M = H + OH + M$,
2. $H_2 + M = H + H + M$,
3. $O_2 + M = O + O + M$,
4. $H + O + M = OH + M$,
5. $O + H_2 = OH = H$,
6. $O_2 + H = O + OH$,
7. $O + H_2O = OH + OH$,
8. $H_2O + H = OH + H_2$,
9. $H_2 + O_2 = OH + OH$,
10. $H_2O_2 + M = OH + OH = M$,
11. $HO_2 + M = H + O_2 + M$,
12. $HO_2 + H_2 + H_2O_2 + H$,
13. $H_2O + HO_2 = H_2O_2 + OH$,
14. $H + HO_2 = OH + OH$,
15. $O + HO_2 = O_2 + OH$,
16. $OH + HO_2 = H_2O + O_2$,
17. $HO_2 + HO_2 = H_2O_2 + O_2$,
18. $H + HO_2 = N_2 + O$,
19. $N + NO = N_2 + O$,
20. $N + O_2 = NO + O$,

The molar reaction rates were calculated using the CHEMKIN-II program package. The calculations were performed in a 3D formulation using an explicit scheme of second-order accuracy with respect to both temporal and spatial variables.

Initially, the proposed approach was tested by 3D calculations for single circular nozzles with diameters of 4 and 2 mm, the results of which were compared...