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Detonation of Low-Density Explosives

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Abstract: Electromagnetic measurements of the particle velocity are performed in a situation when the detonation wave reaches the interface between a powdered high explosive (HE) and a window made of an inert material (Plexiglas). PETN, RDX, and HMX with densities close to the natural bulk density are studied. In order to measure not only the averaged velocity profile, but also possible fluctuations at scales of the order of the HE grain size, small sensors with the working arm length approximately 1 mm are used. In most experiments, profiles with clear chemical spikes are obtained; in some of the measured results, however, the chemical spike cannot be detected on the background of strong signal oscillations, which may be considered as manifestation of the nonclassical mechanism of wave propagation (explosive burning suggested by Apin). Along withour previous study, the present results suggest parallel operation of the shock and convective mechanisms with domination of each mechanism at different segments of the wave front.

Keywords: detonation, explosion, ZND model, explosive combustion.

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INTRODUCTION

Zel'dovich [1], von Neumann [2], and Döring [3] developed the classical model of the detonation wave, known as the ZND model. According to the ZND theory, the agent responsible for detonation propagation is the leading shock wave. The shock is followed by the chemical reaction zone marked by a characteristic decrease in pressure (chemical spike). Owing to its physical transparency, the model has formed a schematic idea of detonation for many decades. Many results in detonation research and explosion applications have been achieved by using the ZND model.

Nevertheless, some new data point to a more complex character of the phenomenon, especially for solid heterogeneous high explosives (HEs), which are of much interest for practice. Detonation waves with the partial transformation in the compression front and with increasing rather than decreasing pressure in the reaction zone were observed in [4, 5]. It was initially assumed that such phenomena are typical for high-density explosives, but similar profiles were later obtained for systems with considerable porosity. In particular, weak detonation regimes were clearly observed in [6], which cannot be led by the shock wave [7].

It is especially difficult to apply the classical model to low-density explosives. The concept of the leading shock wave becomes questionable for powders with porosities of tens of a percent. Instead of the instant shock, one should speak about a compression wave smeared over a mesoscopic scale (approximately equal to the HE grain size) if one-dimensional averaging is used. Under these conditions, jets of a hot gas escaping through the pores from the high-pressure region can become the agent of wave propagation (Apin's concept of explosive burning [8]). Detonation regimes of a convective jet nature were studied in [9, 10] for extremely low-density systems. For RDX grains distributed in a foamy plastic with the density of 0.2–0.6 g/cm^3, the mechanism of explosive burning was definitely confirmed in [11, 12]. The possibility of such a mechanism in a more natural state of explosives of bulk density was noted in [13, 14]. Based on the data obtained in [6, 11–14], it can be expected that convective regimes are not exotic or rare, and systematic search for such regimes is worthwhile.

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In previous investigations, comparatively little attention was paid to mesoscopic effects. The study of Dremin et al. [15] should be noted, where systems in a wide range of densities were tested. With the resolution of about 100 ns available at that time, no particular deviations from the ZND model were observed in low-density charges. Later studies with more advanced experimental techniques mainly dealt with explosives in a homogeneous high-density state. An important range of low and medium densities was not extensively studied by modern methods, though there are some exceptions [6, 11–14].

Ershov et al. [16] used the VISAR diagnostics to study three explosives: PETN, RDX, and HMX with densities slightly higher than the bulk density. The chemical spike (though with a reduced amplitude) was obtained in fine-grain powders (with the particle size of tens of micrometers). However, in coarse-grain powders (hundreds of micrometers), strong oscillations of the flow velocity around the Chapman–Jouguet (CJ) level, similar to the observations reported in [13], were detected approximately in 50% of experiments, while the classical chemical spikes were found in the remaning 50% of the tests. VISAR offers an advantage of local measurements (within the laser spot), which allows flow oscillations to be detected.

The goal of the present work was to compare the results of [16] with the data obtained by the electromagnetic method, which is simpler and more straightforward than the VISAR diagnostics. The same explosives as those in [16] are studied. As the validity of the ZND model was generally confirmed for fine-grain materials, the main attention was paid to explosives with standard particle sizes. The median (in terms of mass) size of HE grains for PETN, RDX, and HMX was 260, 160, and 430 μm, respectively.

EXPERIMENTAL SETUP

The VISAR system used in [16] measured the velocity at the interface between the HE and an inert window made of Plexiglass within the laser spot 0.6 mm in diameter. The electromagnetic diagnostic system had to reproduce these test conditions as close as possible and to trace not only the mean flow velocity, but also its possible fluctuations at scales of the order of the HE grain size. Therefore, very small Π-shaped sensors with the working arm length of about 1 mm were used in the present work. A flat sensor was cut from an aluminum foil strip 9 μm thick, which was glued onto a Plexiglas block 10 mm thick; the operation was controlled microscopically. As in [16], the sensor was protected from the direct action of the explosion products by an epoxy layer 50–100 μm thick. The epoxy layer directly contacted with the end face of the loosely packed HE charge. The process was initiated by a detonator through a small-size plane wave lens at the opposite end of the charge. The arrangement of the sensor plane in the recumbent position and the protective layer ensured sufficient durability of the assembly. The small size of the sensor allowed us to work with comparatively small charges. Charges 18 mm in diameter and 25 mm long in plastic tubes were mostly used in our experiments.

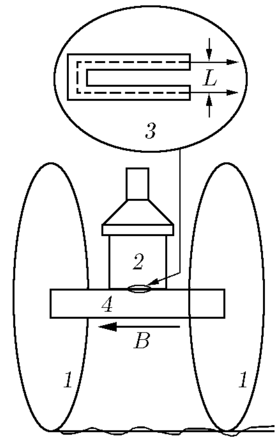

Fig. 1. Experiment geometry: (*1*) Helmholtz coil; (*2*) HE charge; (*3*) electromagnetic sensor; (*4*) Plexiglas block.

A pulsed magnetic field was generated by the Helmholtz coil (two rings with ten turns each, 12 cm in diameter). The current in the coil was generated by a discharge of a 20-μF capacitor at the initial voltage of 3 kV. A standard level of current equal to 1 kA in the maximum, corresponding to the magnetic field inductance $B = 0.15$ T, was reached in 43 μs after discharge beginning. The current can be considered as constant within 1% around the peak at 43±5 μs. Synchronization of the experiment allowed us to set the start of velocity recording much more accurately, and the measured signal duration was approximately one microsecond. The experimental assembly is schematically shown in Fig. 1.

In contrast to standard gauges, the width of the conducting bands of the sensor (approximately 0.4 mm) was not negligibly small. It can be easily seen that the effective size of the gauge under these conditions corresponds to the midline shown by the dashed line in the inset of Fig. 1. Each sensor was accurately measured by a digital microscope, and its effective arm L was calculated as a half-sum of the total width and slot width. The signal from the frame is

$$\mathcal{E} = BLu,$$

where B is the magnetic inductance and u is the measured velocity. The signal level of 0.3 V corresponded to the velocity of 2 km/s.

Synchronized ignition of the detonator was provided by a sufficiently powerful current pulse ($\approx$1 kA). When the detonator was actuated, this current was interrupted, generating oscillations in the a.c. power circuit with a period of about 2 μs, affecting the experimental readings. This problem was solved by feeding the digital oscillograph from a standard uninterruptable power supply, which was disconnected during the experiment. The circuit was grounded at one point where the braid of the cable transmitting the signal was connected to the gauge.

One more source of noise and interferences is polarization of the material within the wave front. Figure 2a shows the signal recorded under the conditions described above. Before the main signal pulse rise, one can see fluctuations induced by the separation of charges near the wave front. In fact, the edge effect outside the "capacitor" formed by this separation is initially observed. When the front reaches the protective layer boundary, the charges are redistributed, which is responsible for significant alternating-sign oscillations during 20–30 ns. As this disturbance is of a capacitive character, the epoxy layer cannot reduce this noise. The noise amplitude is of the same order as that of the useful signal, which begins when the pressure wave reaches the sensor. The noise observed on the profile at later times is associated with flow inhomogeneity at the scale of the HE grain rather than with electrostatic effects. To suppress polarization noise, following [17, 18], we placed a grounded electrode (aluminum needle 0.6 mm in diameter) at a distance of about 2 mm upstream; the needle axis passed approximately at 3 mm from the sensor arm. The effect of this measure is illustrated in Fig. 2b. It is seen that the polarization noise almost vanishes by the instant when the main signal appears.

Figure 2c shows the signal recorded in the case without the protective epoxy layer. On the background of intense oscillations, it is practically impossible to distinguish any specific features of the useful signal (though the positive mean level approximately corresponds to the CJ state). In contrast to polarization noise, which can be successfully eliminated by using the grounded needle, the charge separation in the present case is observed in the wave front plane. Moreover, such oscillations were also observed in the absence of the magnetic field (naturally, without the positive mean level). Therefore, these oscillations are not generated by electromagnetic effects (e.g., because of oscillations of the velocity of conducting gases near the sensor); they are induced by chemical processes. In the reac-

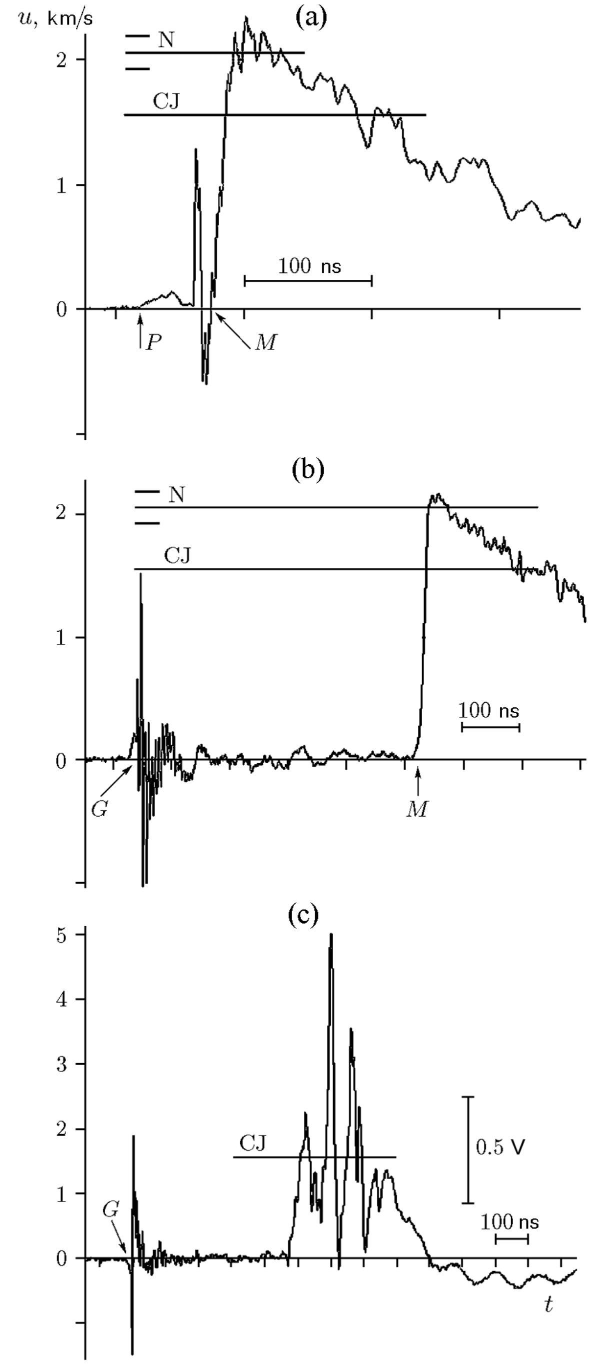

Fig. 2. Interface velocity profiles in the case of PETN charge detonation (the initial density is 1 g/cm^3): (a) experiment without the grounding needle; (b) discharge of polarization on the needle protruding by 2.25 mm from the sensor plane; (c) experiment without the protective layer; P is the beginning of polarization interference, M is the beginning of the main signal, G is the instant of front grounding, CJ is the expected level of the velocity in the Chapman–Jouguet state, and N is the velocity interval expected for the Neumann peak and the mean value in this interval.

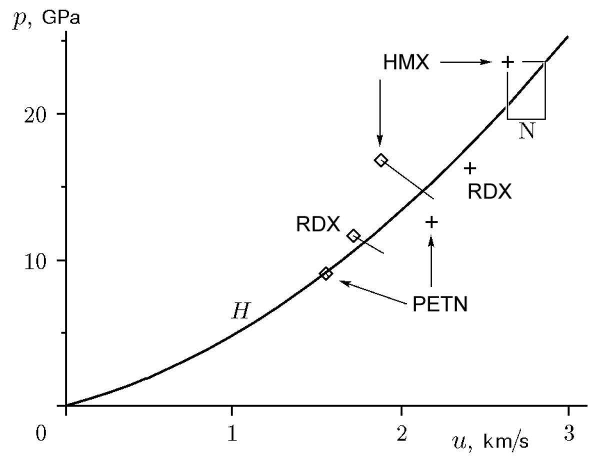

Fig. 3. P–u diagram of the experiments: H is the shock adiabat of Plexiglas, the CJ states for three explosives are marked by diamonds, the estimated values of the Neumann peaks are marked by the plus signs, and N is the interval of possible velocities in the case of HMX unloading from the Neumann peak.

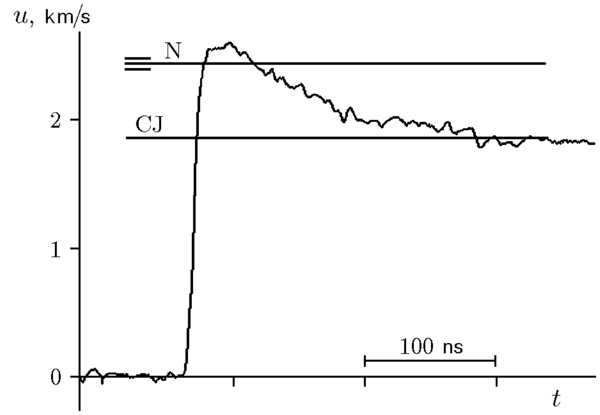

Fig. 4. Interface velocity profile in the case of RDX detonation (the initial density is 1.1 g/cm^3).

tion zone of an inhomogeneous medium, it is natural to expect potential fluctuations at a level of several tenths of a volt. The small resistance of the sensor should actually short-circuit these chemical electromotive forces, but an unprotected sensor is rapidly disrupted, opening the way to disturbances observed in experiments. Thus, the protective epoxy layer not only simplifies charge assembling and increases the life span of the sensor, but also prevents the emergence of noise arising due to a direct contact of the gauge with the reacting HE.

Similar to [16], the experimentally measured profile is compared with the velocity level generated by the calculated CJ state in the window material. Figure 3 shows the shock adiabat of Plexiglas [19] (the relation between the shock wave velocity D and particle velocity u is $D = 2.59 + 1.52u$ [km/s]), and also the CJ states for three explosives calculated on the basis of the data [20], as well as the corresponding release lines. It should be noted that all CJ states are close to the shock adiabat, which means that possible errors of recalculation are sufficiently small. Moreover, Fig. 3 also shows the expected states in the Neumann peak under the assumption that the ZND model is valid. As there are no reliable data on these states, they were obtained by somewhat arbitrary multiplication of the pressure and velocity by a factor of 1.4. The data on dynamic unloading from the Neumann peak are unavailable either; therefore, we estimated the interval where the peak velocity of the interface could be located. This interval is determined by the horizontal and vertical lines drawn from the peak point to the adiabat; these lines are drawn in Fig. 3 for HMX. For bulk densities, the peak states are also close to the Plexiglas adiabat, and the resultant intervals are fairly narrow. Both experiments whose results are shown in Figs. 2a and 2b demonstrate that the Neumann level is reached. It is seen that the measurement accuracy (about 5%) is sufficient for chemical spike detection. A more conventional procedure of detecting the chemical spike on the background of a slowly changing profile (in particular, the profile inflection) cannot be applied in our case because of oscillations observed, e.g., in Fig. 2a.

The minimum signal rise time in the experiments was about 5 ns. The experimental resolution estimated on the basis of the time of wave travelling in the sensor was also close to 5 ns.

EXPERIMENTAL RESULTS

Profiles with chemical spikes were consistently obtained for RDX in six experiments. As is seen from Fig. 4, the peak velocity agrees well with the estimated value and is noticeably higher than the CJ level. This is fairly consistent with the ZND model. The same result was obtained in [16]. RDX had the smallest grain size among the three explosives considered in the present study. Correspondingly, convective processes in RDX were less probable. The working arm of the frame could accommodate 10–20 particles; therefore, the action of the wave front on the sensor was effectively averaged. As a result, the noise on the oscillograms was not high.

For HMX, which had the largest particle size, both the classical profiles (Fig. 5a) and the profiles with random oscillations (Fig. 5b) were observed. In this case, the working arm of the sensor could accommodate only 2–3 HE particles, which was responsible for oscillations on some curves. In two experiments of [16], one clas-

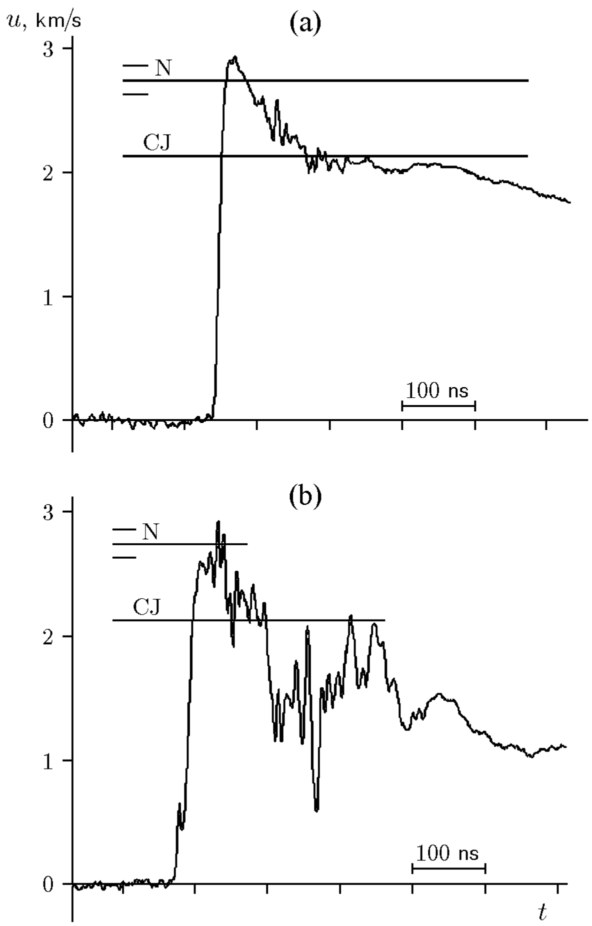

Fig. 5. Interface velocity profiles for HMX (the initial density is 1.28 g/cm^3): (a) profile with the chemical spike; (b) nonclassical profile.

sical curve was obtained, whereas the other profile had clearly expressed oscillations. Electromagnetic diagnostics revealed deviations from the ZND model in two cases out of six. The pulse front was not steep, and the oscillations occurred during the first 100 ns between the CJ and Neumann levels, as in Fig. 5b. Such a regime can be optionally considered as a hybrid rather than convective regime.

Out of seven electromagnetic experiments with PETN, six tests were more or less consistent with the ZND model. The profile could be somewhat noisy, as that in Fig. 2a. The size of PETN particles lies between the grain sizes of HMX and RDX; therefore, approximately six PETN particles could be accommodated on the gauge arm. Apparently, it was sufficient for averaging the oscillations, though the noise on the curves was still noticeably more intense than that in the case of RDX. One of seven experiments yielded a result similar to that illustrated for HMX in Fig. 5b. In [16], both experiments with coarse-grain PETN revealed strong

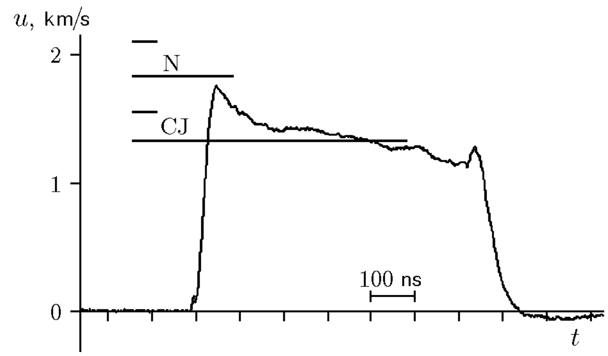

Fig. 6. Interface velocity profile for fine-grain RDX.

oscillations. It can be assumed that the VISAR diagnostics is more sensitive to flow velocity fluctuations.

Similar to [16], the experiments with fine-grain explosives yielded smooth profiles with clearly expressed chemical spikes. Figure 6 shows the result of the RDX experiment with the mean particle size of 11 μm and initial density of 0.8 g/cm^3. Similar results were obtained for fine-grain HMX (with the particle size of 21 μm) and PETN (80 μm). The classical profile was also obtained for a plastic explosive based on fine-grain PETN. Naturally, convective processes become less important in the case of a small grain size and, moreover, in solid plasticized explosives.

DISCUSSION

The structure of bulk charges implies a random spatial distribution of HE grains and pores. Therefore, the wave front is inevitably inhomogeneous, and convective phenomena are also inevitable at the grain size scale. However, the following question arises: Which processes play the key role?

A necessary attribute of the ZND regime is a clearly expressed chemical spike following the shock wave. Correspondingly, the features typical for the nonclassical regime are a smooth increase in the parameters at the wave front (in particular, the presence of a "precursor") and the absence of the chemical spike [11, 12]. A similar approach was also used in [14]. It should be noted that the velocity markers in those works were sufficiently thick foils (100–400 μm), which could deteriorate detection of fine details of the process. In the present work, similar to [16], we used significantly thinner small-size sensors capable of detecting not only the mean parameters of the waves, but also the random oscillations expected to appear in the convective process, which should be also considered as indicators of the nonclassical regime.

At first glance, the ZND approach does not seem suitable for loosely packed powders. It was surprising that the classical model turned out to be applicable in most experiments. Despite the porous structure of the material with a lot of empty space, which is favorable for convective processes, the majority of the profiles revealed a drastic increase in velocity above the CJ level and its subsequent reduction. A possible explanation for this result implies rapid fragmentation of particles in the compression front and fast compaction up to closing of the pores. The characteristic time of such processes can be naturally estimated as the ratio of the grain size d to the wave velocity D, i.e., 50–60 ns for HMX and PETN and approximately 30 ns for RDX. In our experiments the pulse rise time was 5–30 ns, which was 2–4 times smaller on the average than the value expected for a given grain size. This shows that homogenization at the grain size scale occurs unexpectedly rapidly, which allows one to use the shock wave concept for bulk density explosives (with some constraints). The scatter of the rise times is apparently associated with the details of material grain packing in the vicinity of the sensor. The measurement accuracy is sufficient for definite identification of chemical spikes.

The oscillations observed in the velocity signals for coarse-grain explosives do not necessarily testify to the jet regime of wave propagation. Waves generated by more and more distant segments of the interface reach the sensor as the time progressed. The natural delay of such signals, which contains the stochastic component among others, can create a false impression of long-time oscillations on the interface. The analysis of the sensor response to flow inhomogeneities will be performed in the future. It should be preliminary mentioned that sensors with sufficiently large areas are expected to ensure effective averaging of the delayed oscillations. The sensors used in the present work, which are comparable with the grain size, allowed us both to determine the mean values and to observe the flow fluctuations. As noticeable oscillations were observed only in some experiments, they should be considered as the manifestation of real processes in the wave front rather than the effect of the retarded fluctuations.

CONCLUSIONS

The results of the present work combined with those obtained previously in [16] testify to the possibility of the jet mechanism of detonation propagation in loosely packed charges. At the same time, it should be recognized that the results obtained in the study cannot be considered as an undoubtful proof of the convective mechanism. The flow oscillations and the smeared front testify that two-phase processes are essential, but it does not mean that the jets are the main factor of reaction initiation. Such a conclusion requires additional arguments (e.g., the absence of contacts between the particles in rarefied media studied in [12]). In contrast to the classical ZND pattern, the jet model cannot be one-dimensional. For this reason, it is rather difficult to develop a theory that can be compared with experimental data. At the moment, there is no clear indicator in the jet model (such an indicator in the ZND model is the chemical spike). Nevertheless, the jet model is an interesting concept, which deserves much attention.

Observations of different regimes under fairly close test conditions in [16] and in the present work suggests a possibility of a hybrid character of detonation propagation in loosely packed explosives; in this case, the leading factor of detonation propagation at different segments of the wave front can be either the shock wave or the convective processes.

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