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Unidirectional Propagation of Gas Detonations in Channels with Sawtooth Walls

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Unidirectional Propagation of Gas Detonations in Channels with Sawtooth Walls

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Abstract

We study the detonation propagation in a channel geometry that suppresses detonation propagation in one direction, allows it in other direction, and does not create flow restrictions in the channel. The geometry consists of a series of divergent sections separated by wedges that form a sawtooth shape. Numerical simulation show that the detonation fails to propagate through this geometry in one direction because the detonation front is weakened by diffraction, and reignition centers are isolated from the main channel. In opposite direction, convergent parts of geometry support the detonation propagation.

1. Introduction

A detonation wave ignited in a geometrically unconfined homogeneous reactive gas mixture usually spreads in all directions from the ignition point. For a confined system, the detonation propagation may be affected by the confinement geometry, which can, in some cases, lead to detonation failure. Geometries that cause detonation failure are often used in detonation arresters [1] to prevent the detonation from propagating through industrial pipelines. Detonation arresters are usually designed to stop both detonations and deflagrations, and the resulting geometries are often complex and create significant flow restrictions. If we focus only on quenching detonations, there are a few relatively simple ways to decouple the flame from the shock without putting obstructions in the flow.

One way to prevent a detonation from propagating through a channel is to line the channel walls with a porous material that damps transverse waves [2-4]. This weakens and destroys triple-shock configurations that are largely responsible for the energy release in a gaseous detonation wave, and the detonation eventually fails. This method prevents the detonation propagation in both directions and does not create flow restrictions in the channel.

Another way is to use detonation diffraction phenomena that may quench a detonation propagating from a smaller to a larger channel [5-20]. For example, inserting a cylindrical expansion section of a larger diameter into a pipeline may stop a detonation if the pipeline diameter is small enough. Experiments show that the detonation exiting from a tube to a large volume fails when the tube diameter is smaller than approximately 13 detonation cells [7-8,10]. For a limited expansion section, however, the detonation can reignite when shocks produced by the failed detonation reflect from walls. These shock reflections may ether ignite a new detonation directly or promote a deflagration-to-detonation transition (DDT) in the expansion section. The probability of DDT may even increase for a larger expansion section, thus making this simple geometry unreliable for detonation quenching.

In this paper, we consider a more complex geometry that relies on detonation diffraction phenomena observed in divergent channels [6, 11-13,17-18] to quench detonations propagating in one direction. We analyze the detonation propagation and extinction in a channel with a sawtooth shaped wall using two-dimensional (2D) numerical simulations.

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2. Channel Geometry and Detonation Quenching

The 2D channel geometry shown in Fig. 1 consists of three consecutive divergent sections that create a sawtooth shape on the top wall. The bottom wall is flat, but it can also be considered as a symmetry plane for a larger channel with sawtooth sections on both walls. Sections are separated by wedges that are designed to play several roles.

First, each wedge forms the wall of the next divergent section that causes a diffraction of detonation front propagating from the left to the right. Experiments with divergent channels [6,11-13,17-18] show that diffraction weakens the front so that the shock and flame decouple if the angle α is large enough.

Second, the wedges are sharp and pointed roughly perpendicular to the diffracting detonation front, as shown in Fig. 1. This minimizes the probability of ignition when the shock hits the tip of the wedge.

Third, a pocket of gas above each wedge becomes isolated from the rest of the unburned material when the flame reaches the tip of the wedge, as shown in Fig. 1. If the shock and flame are decoupled, shock reflections in the pocket may trigger a new detonation in the pocket, but it will not spread to the channel. The exact shape of the pocket is not important, but it should be deep enough to allow the flame to reach the tip before the shock reaches the end of the pocket.

Thus, the sawtooth geometry shown in Fig. 1 causes the detonation to continually weaken as it propagates in one direction through a series of divergent sections, as shown in the numerical simulation below. This geometry is not designed to prevent a detonation from propagating in the opposite direction. The geometry is still relatively simple and does not obstruct the flow through the channel. The geometry parameters specified in the caption of Fig. 1 were determined in a series of numerical simulations similar to the one we describe here.

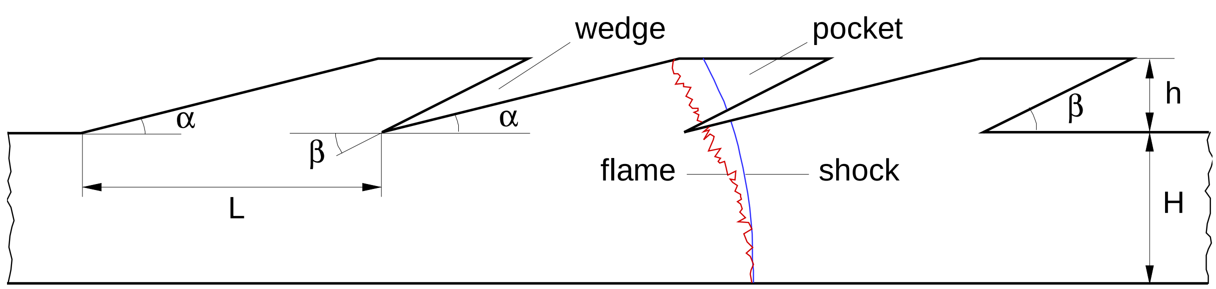

Fig. 1. Channel geometry. H=1 cm, h=0.5 cm, L=2 cm, $\alpha = 14\,^\circ$, $\beta = 27\,^\circ$.

3. Numerical Model

The numerical model is similar to the model used in [21]. Here, however, we solve the reactive Euler equations and neglect molecular transport processes. The equations are solved on an adaptive Cartesian mesh using a second-order Godunov-type numerical method that incorporates a Riemann solver. The reactive system is described by a one-step Arrhenius kinetics of energy release. The model parameters summarized in [21] approximate a stoichiometric hydrogen-air mixture at 1 atm. Computations were performed with the minimum computational cell size $\mathrm{dx}_{min} = 1/2048$ cm, which corresponds to 39 computational cells per half-reaction zone length of ZND detonation x_d.

Detailed numerical simulations [21] of a quasi-steady state detonation in this system performed with the same numerical resolution show a very irregular detonation cell structure with a typical cell size 1–2 cm, which corresponds to 50–100 x_d. A fine cellular substructure was observed as well, which is expected for the system with the high activation energy $\mathrm{E}_a/\mathrm{RT}_{ZND} = 13.4$.

To model the detonation propagation through the geometry shown in Fig. 1, we began with a channel 14 cm long and mostly 1 cm high, with the sawtooth geometry spanning 6 cm in the middle of the channel. This means that the first divergent section starts 4 cm from left end of the channel. The channel is closed at both ends and filled with the reactive mixture.

The detonation was initiated near the left end of the channel by placing three small circular areas of burned material in front of a Mach 5 planar shock. By the time the detonation reached the divergent section, it was propagating with a velocity close to D_{CJ} and developed a cellular structure independent of the initial perturbation. The detonation remained slightly overdriven in the sense that the cell size was smaller than the average 1–2 cm expected for this system [21]. This provided a relatively consistent set of initial conditions for detonation diffraction in the system with a highly irregular cell structure.

4. Results of Computations

The evolution of a detonation wave propagating through the sawtooth section is shown in Fig. 2. As the detonation enters the divergent part of the channel, the lateral rarefaction begins to weaken transverse waves and increase the detonation cell size. The same phenomena were observed in experiments with divergent channels [6,11-13,17-18]. This weakening effect is not always obvious in the simulations due to the irregularity of the cell structure, but it does weaken the detonation front. By the time the front reaches the tip of the first wedge, the upper part of the front weakens to the point where the flame decouples from the shock.

The interaction of the leading shock with the sharp tip of the wedge, both sides of which are roughly perpendicular to the front, does not produce any strong reflected shocks. Once the wedge penetrates the detonation front, the two parts of the front on both sides of the wedge become independent on each other. The upper part continues to propagate into the closed pocket above the wedge. Eventually, this produces a new detonation and a powerful reflected shock, but these never reach the lower part of the front. The lower part continues to propagate into the second divergent section and gradually weakens. Due to the irregularity of the detonation front, this weakening is also irregular and non-uniform in the sense that random parts of the front may become weaker or stronger at different times.

When the front reaches the second wedge, the upper part of the front happens to be the strongest. The wedge cuts the upper part from the weaker lower part, thus weakening the lower part even further. Again, the lower side of the wedge is practically perpendicular to the leading shock and does not create any new transverse waves in the lower part of the front. The upper part of the front burns all the material in the pocket, but this does not affect lower part.

In the third divergent section, the detonation front weakens considerably, and the flame completely decouples from the shock. Since this is the last section, the lower side of the last wedge is horizontal and is not perpendicular to the diffracting shock. The shock reflection at this side creates a Mach stem, which is, however, too weak to ignite the material. The decoupled flame that propagates with the flow behind the shock also reaches the tip of the wedge, thus separating the unburned material in the pocket above the wedge from the unburned material in the channel. When the upper part of the shock above the wedge reaches the end of the pocket and ignites a detonation, this detonation cannot spread into the channel. Thus, the detonation in the channel is quenched. The weakening inert shock continues to propagate through the channel as the distance between the flame and the shock increases.

Figure 3 shows the detonation propagating through the sawtooth section in the opposite direction. In this case, the detonation survives. Even though the diffraction at each wedge considerably weakens the front, subsequent reflections with oblique walls that form convergent sections create powerful transverse waves. These waves help the detonation propagation (28 μs) or reignite it (38 μs). As a result, the detonation exiting the sawtooth section is as healthy as the one entering it.

5. Discussion and Conclusions

We have described a channel geometry that allows detonation propagation only in one direction and does not create flow restrictions in a channel. In one direction, the detonation quenching is achiveed using divergent sections to weaken the detonation front through the detonation diffraction. The detonation reignition is suppressed by wedges that isolate reignition centers from the main front. In other direction, the detonation propagation is supported by convergent walls.

The geometry described here was optimized using an extensive series of numerical simulations in which the sizes and angles of the sawteeth were varied. All of these simulations were performed for one particular reactive system, described by a simplified reaction model that approximates a stoichiometric hydrogen-air mixture and produces a realistic irregular detonation cell structure typical of many practical fuel-air mixtures. From this, we expect the same type of geometry to quench detonations in other mixtures as well, though optimum geometrical parameters may be different.

The stochastic behavior of detonations with irregular cell structures means that for each simulation or experiment, detonation diffraction occurs in a slightly different way. Thus different numbers of sections may be required to quench the detonation. Increasing the number of sections usually helps, but too many sections may lead to the flame acceleration and DDT similar to that observed in channels with obstacles [21].

To date, the unidirectional detonation propagation in channels with sawtooth walls was demonstrated only in numerical simulations. Future experiments will examine whether these types of geometries can be used to quench actual detonations.

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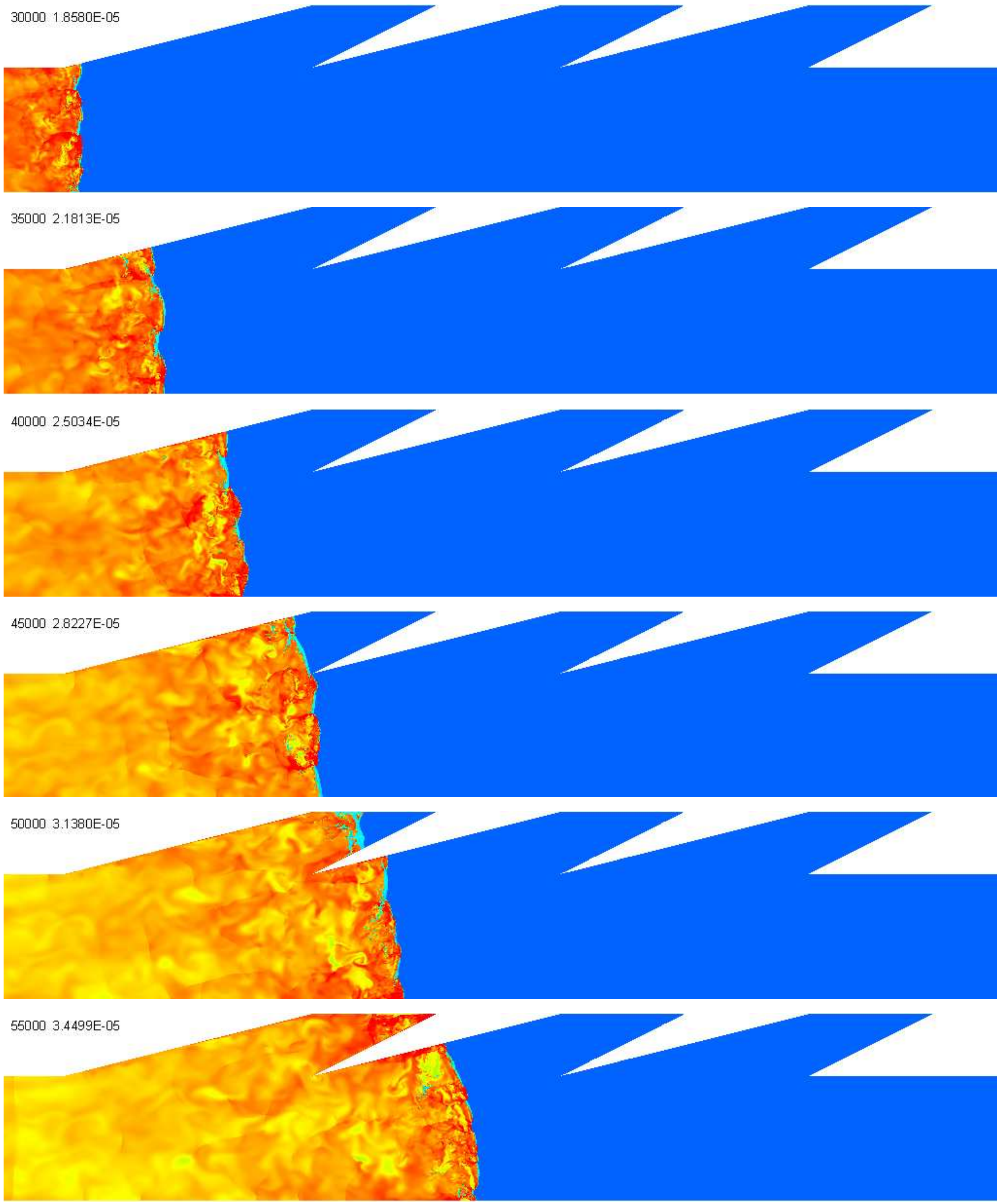
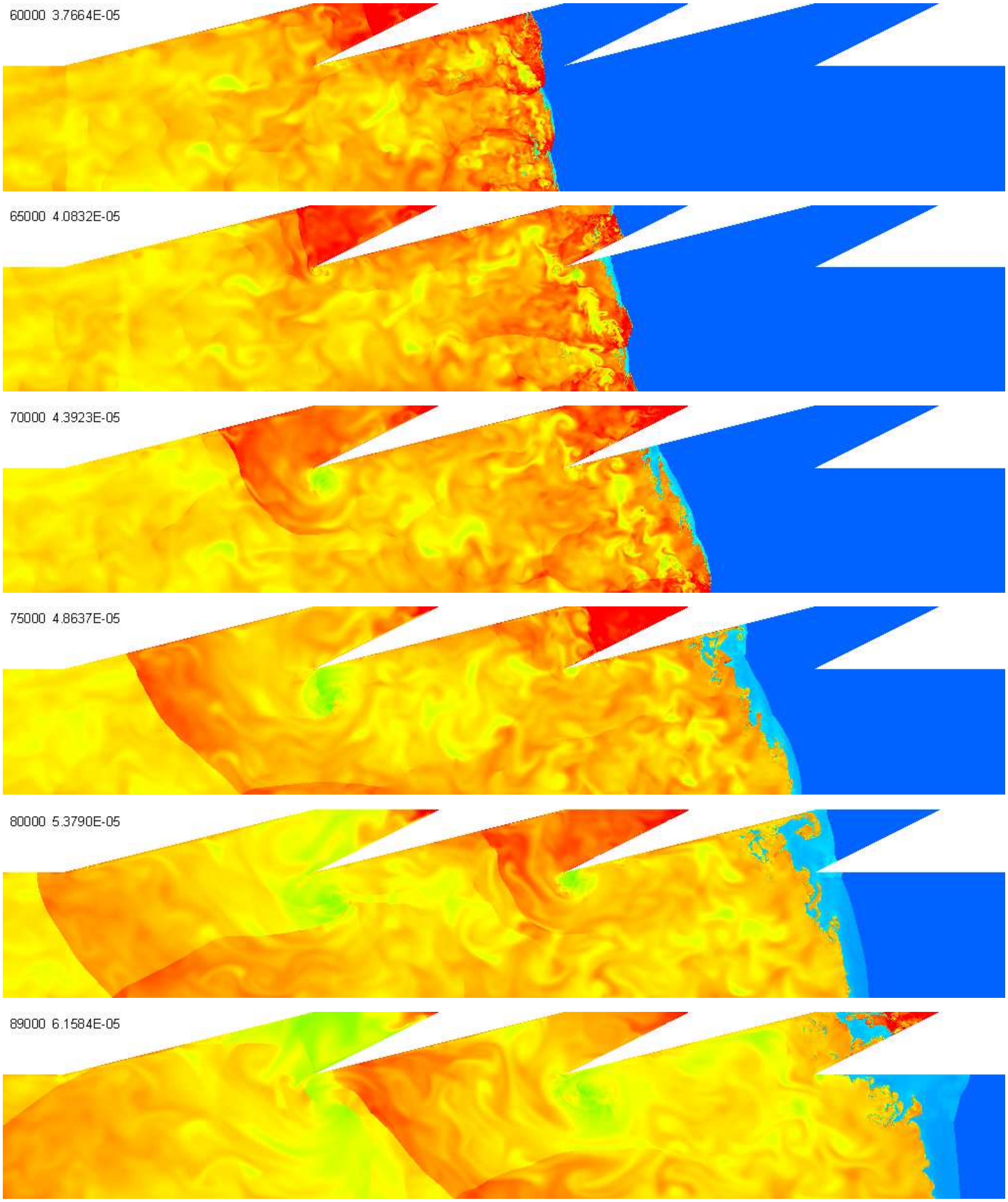


Fig. 2. (*continued on next page*) Detonation propagation through sawtooth geometry. Timesteps and times in seconds are shown in frame corners. Colors show temperature (see colormap in Fig. 3)



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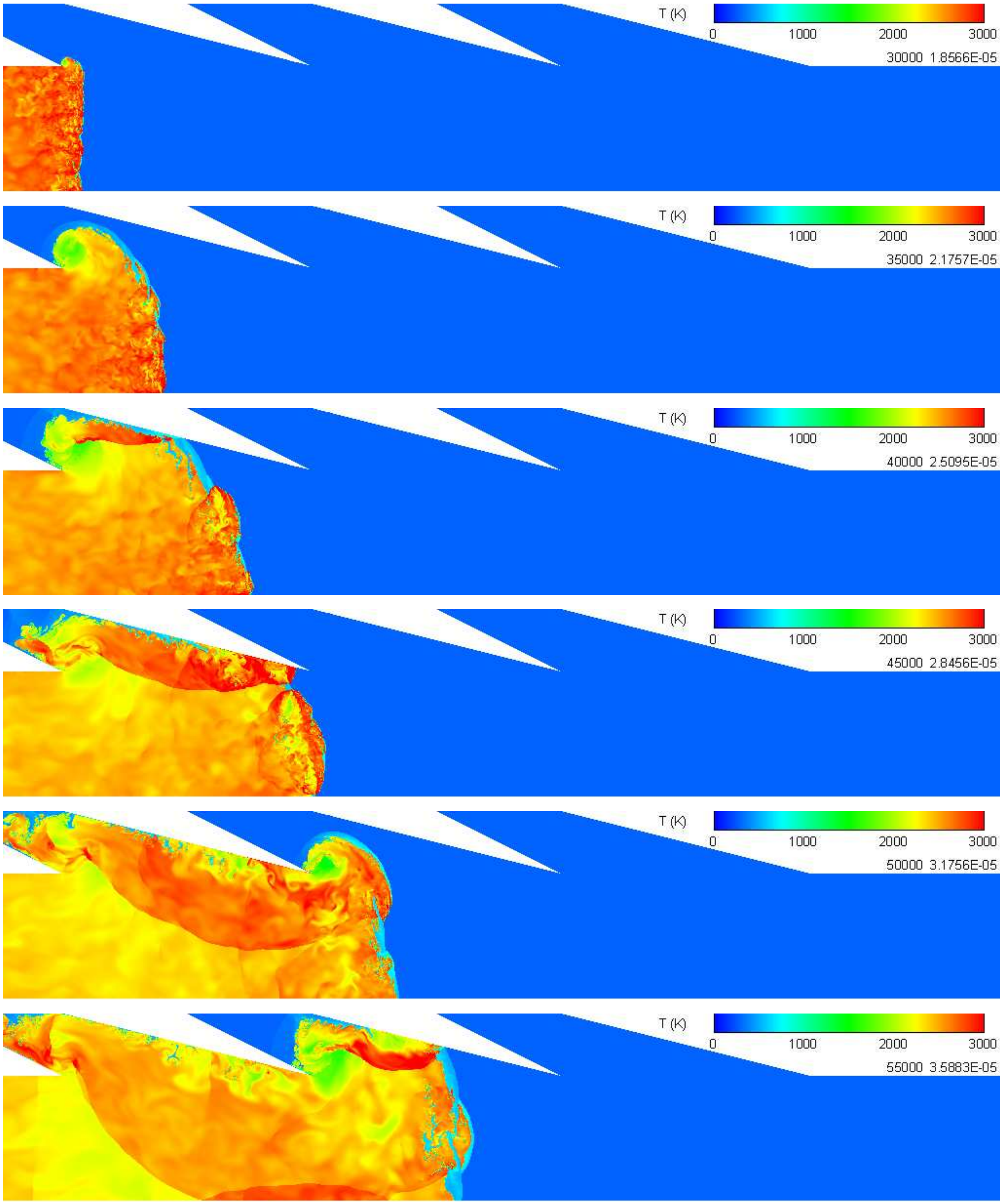

Fig. 3. (*continued on next page*) Detonation propagation through sawtooth geometry in opposite direction. Timesteps and times in seconds are shown in frame corners. Colors show temperature.

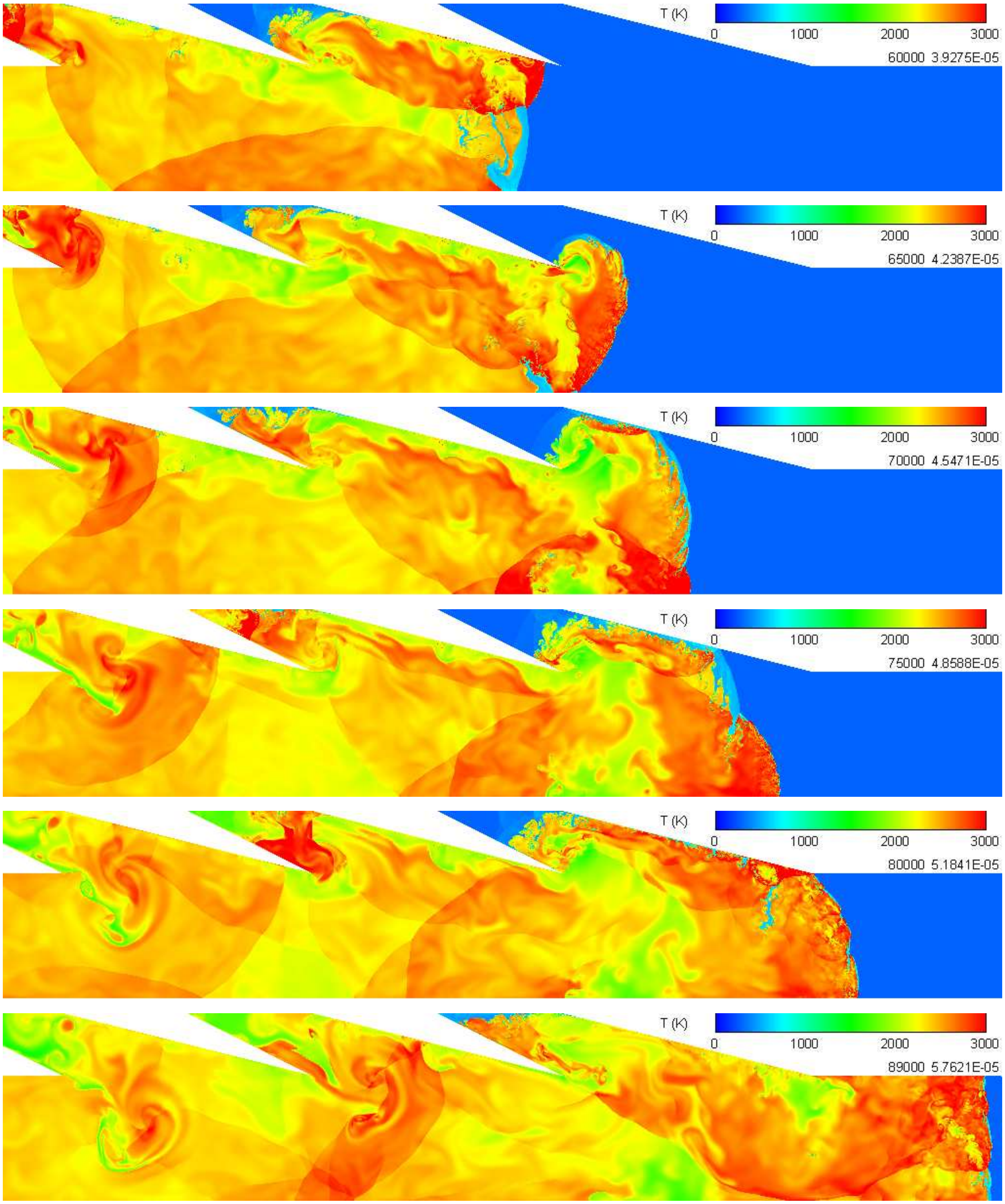

Fig. 3. (*continued*) Detonation propagation through sawtooth geometry in opposite direction. Timesteps and times in seconds are shown in frame corners. Colors show temperature.