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Technical Notes

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Detonation Initiation by Annular-Jet-Induced Imploding Shocks

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Introduction

DEVELOPMENT of reliable detonation initiation methods that require low energy and no chemical additives or additional fuel components is a crucial issue in the development of detonation-based propulsion devices such as pulse detonation engines (PDEs). There have been numerous studied dealing with different fundamental and applied aspects of detonation initiation, and a detailed review is beyond the scope of this Note. Comprehensive reviews on detonation initiation for PDE applications can be found in Refs. 1–3. Those reviews indicate that neither direct initiation nor initiation of a flame followed by a deflagration to detonation transition (DDT) is practical for propulsion engines such as PDEs as a result of initiation-energy or DDT-length restrictions. Chemical additives including oxygen can lower the energy required for direct initiation or reduce DDT distance but require additional storage and handling systems, which are undesirable for propulsion applications. Also, flow-blockage structures of various shapes can be placed in the PDE tube to reduce the DDT distance by enhancing turbulence in the DDT process. However, such flow obstacles reduce the PDE performance and might not be durable for sustained multicycle operations. In addition, predetonators or detonation initiators of different types have been explored, in which detonation is initiated in a small chamber typically containing a readily detonable mixture and then propagates into the main chamber containing the primary mixture.[4] Difficulties with this approach include failure during the diffraction or transition process and the need for additional, more detonable fuel components or chemical additives and associated design complications.

In addition to just-mentioned approaches, other methods based on more complex mechanisms have also been looked at. These include, hot turbulent jets,[5–9] two-stage ignition involving hot radicals and shock focusing,[10] and various geometries for enhancing shock focusing effects.[11] A promising approach is to use imploding small-scale detonation waves or imploding shock waves to directly initiate detonations. In a recent work,[12] multiple, small, and separated detonation fronts were combined in the focusing region to initiate a detonation covering the entire cross section of a larger tube. However, in this approach the detonations were still needed to be generated separately in small tubes filled with an easily detonable mixture by spark plugs. In addition, a complex tubing system was required to synchronize arrival times of the detonation fronts from each tube at the focusing region. In our recent work,[2] the possibility of using jets of different configurations of fuel, air, or oxygen at modest temperatures (>500 K) for detonation initiation was explored, and the results were mixed. Different two-dimensional jets used in the study were not able to initiate any detonations in two-dimensional channels filled with a stoichiometric ethylene-air (C2H4:O2:N2/1:3:11.28) mixture, but the triannular jets of alternating air fuel air angled towards the endwall were able to initiate detonations under some conditions. It was shown that there were three major factors affecting this jet detonation initiation process: 1) combustion among jet materials, 2) annular-jet-induced cylindrically imploding shock, and 3) reflected shocks from the end- and sidewalls. However, the relative importance of each affecting factor remains unclear from that study. Following the previous study, in this Note we will establish the relative importance of the three factors. Further, based on understanding gained, we will present an initiation concept that is simple to implement and imposes minimal additional engineering complications to the PDE systems.

Basic Concept

We must first resolve the remaining critical issue from our previous study,[2] that is, the relative importance of different contributing factors in the detonation initiation process. If combustion among the jet materials is the dominant contributing factor, multiple jets of different fuel components from different injection directions might be needed to optimize the mixing and combustion among the jet materials, which can significantly complicate the PDE system and result in requiring additional fuel components or additives. If the reflected shocks are important, the initiation time might be too long for the PDE applications because those reflected shocks take some time to develop because they are generated after the imploding shocks impact on the end- or sidewalls. However, if an annular-jet-induced cylindrically imploding shock is capable of initiating detonation alone, the chemical composition of the jet material becomes largely irrelevant, and the jet configuration can be quite simple. Indeed, as we will show next, the imploding shock is by far the dominant contributing factor. Imploding shocks generated by annular jets at modest conditions can create sufficiently large kernels of temperature and pressure high enough to initiate detonation. Figure 1 shows a schematic of the detonation initiation concept proposed in this study. In the figure, only one single annular jet is used. The jet material can be either the existing fuel for the propulsion system or air, completely avoiding any additional fuel components or additives,

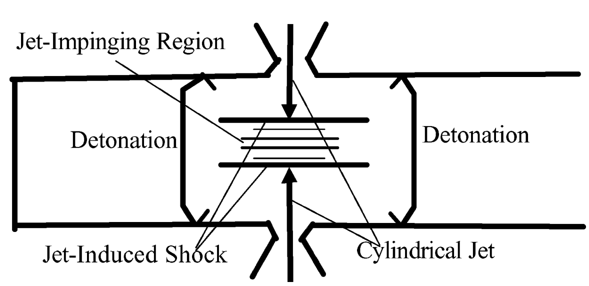

Fig. 1 Schematic of the initiation process by an annular-jet-induced cylindrically imploding shock.

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such as oxygen. Because air at modest pressures and temperatures can be directly obtained from the engine inlet after minimal compression, it is the preferred jet material for airbreathing applications.

Validation by Numerical Simulations

We validated this detonation initiation concept using multidimensional, time-accurate numerical simulations. First, we will briefly discuss the physical models and numerical methods used in the simulations. Second, we will use results from a typical numerical simulation of the detonation initiation process using this concept to illustrate basic features and their development during the initiation process. Third, we will quantify the jet parameters needed for successful detonation initiation and summarize several general trends in this jet initiation process based on our numerical studies, which is valuable for future experimental effort to further verify this initiation concept.

Physical Models and Numerical Methods

In the simulations, the conservation equations for mass, momentum, energy, and individual species are solved in conjunction with a two-step induction-parameter model.[13] The induction-time data, on which the induction parameter is based, were obtained from shock-tube experiments.[14] The convective part of the conservation equations is solved using the flux-corrected transport algorithm.[15] In the simulations, the virtual-cell-embedding[16] technique is used to accurately represent the complex jet configurations and geometric shapes of the PDE tube in the orthogonal mesh. In this study, our main focus is on the shock-induced detonation initiation, where diffusive transport processes and radiation transport have relatively much weaker effects than strong pressure gradients because of the shocks and energy release from the combustion process, and hence are neglected. These numerical methods, physical models, and related model parameters have been validated for detonation-applicable conditions and extensively used in detonation related studies (e.g., Refs. 13, 17–19). More detailed discussion of these models and methods can also be found in those references. However, the induction parameters based on limited available experimental data have significant uncertainties. Although the parameters used have been validated against the detonation pressure and velocity extensively, and against detonation cell size and transition condition to a lesser extent, this uncertainty might still have some quantitative effects on the simulations presented here. Unfortunately, at present, there are not that many experimental data available for calibrating the model parameters for conditions relevant to PDE applications, against which one can directly validate those models parameters. More research effort is needed in this area.

Here, we numerically simulate the detonation initiation process by an annular jet injected into a PDE tube filled with a stoichiometric ethylene-air mixture (C2 H4:O2:N2/1:3:11.28) at 1.0 bar and 300 K. The tube diameter is 14 cm, and the width of the jet slot is 2.25 cm. Objectives of the simulations are 1) demonstrating basic features in this initiation process and 2) establishing minimal values of the overall jet parameters, that is, pressure, temperature, and velocity, necessary for detonation initiation. In the simulations, computational cell size is 2.5 mm. In addition, a finer cell size, 1.25 mm, is used in some cases to verify grid independence of the basic flow features and overall jet parameters from the simulation. The corresponding grid systems for the two cell sizes are $60 \times 60 \times 180$ and $120 \times 120 \times 360$, respectively. The simulations using those two

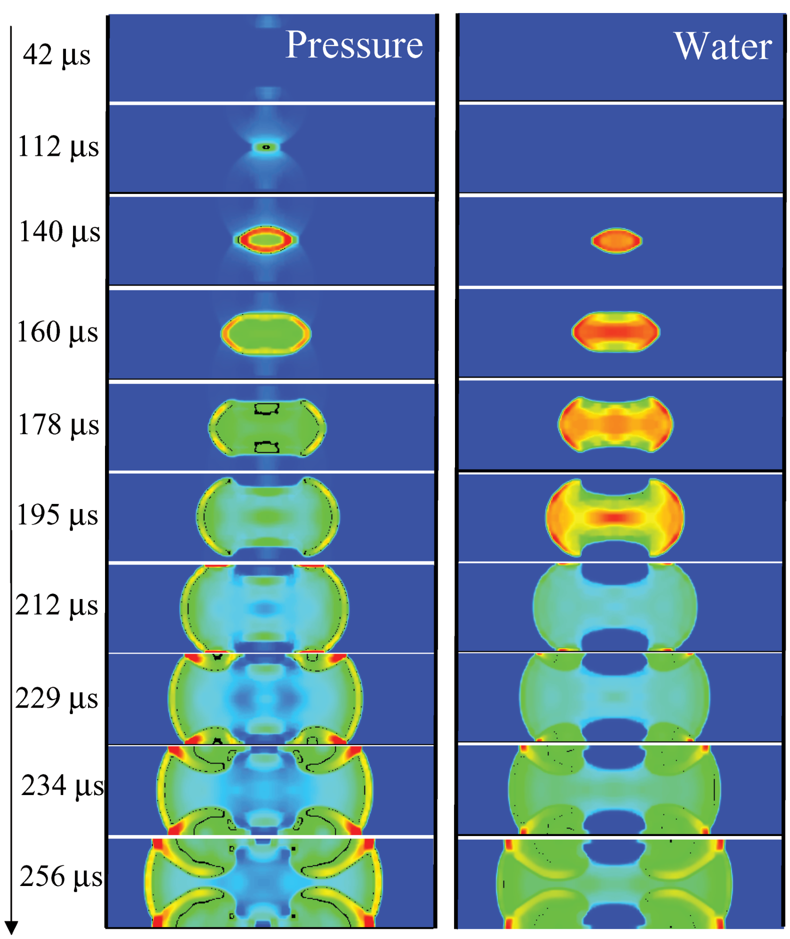

Fig. 2 Contours of pressure and water concentration from a simulation of the detonation initiation process by an annular-jet-induced cylindrically imploding shock in a ethylene-air stoichiometric mixture (C2 H4:O2:N2/1:3:11.28).

resolutions showed very similar basic flow features in the initiation process and values of the overall jet parameters, such as minimum jet pressure and temperature needed for successful detonation initiation. This is an indication that grid independence is achieved for the overall initiation process in the simulations. Although the used grid resolutions are sufficient for our objectives of this technical Note just stated, they are not quite adequate for detailed detonation structures, especially at the initial stage of the initiation process considered here. Immediately after the annular jet collides into itself, the temperature and pressure near the collision center are higher than 150 atm and 3000 K, respectively, in the cases studied here, which result in detonation structures of extremely small scales; accurately simulating three-dimensional detonation structures of such small scales is beyond the objective and scope of this limited technical Note.

Basic Features and Their Development

Figure 2 shows development of the detonation initiation process by an annular jet injected at a pressure of 2.0 bars, temperature of 250 K, and Mach number of unity. In this figure, the pressure and water concentration snapshots were taken on a centerline plane in the tube at different times. The annular jet is initiated at the time mark 0. The jet impinges on to itself near the tube centerline at 112 μs, and a high-temperature-pressure kernel begins to form. However, there is no water production until 140 μs. At 140 μs, a high-temperature-pressure kernel of elliptical shape is observed. The pressure in the kernel is above 50 bars, and water emerges. At the edge of the kernel, the pressure is very high (>100 bars), and a detonation front begins to form. At 160 μs, the kernel expands, and the pressure at the edge around the kernel reduces somewhat to a level corresponding to a slightly overdriven detonation in the given mixture (C_2H_4:O_2:N_2/1:3:11.28). At 178 μs, the kernel further expands. However, at this time the detonation is only observed at either end of the kernel, and two detonation fronts mainly propagate along the longitudinal direction of the tube towards both tube ends. The part of the detonation front on the side of the kernel is quenched by the air brought in by the jet and becomes a nonreactive shock. Beyond 178 μs, the jet air is entrained and mixed with the combustion products from the detonation process, reducing the water concentration level around the side of the kernel. At 195 μs, the detonation fronts at the two ends of the kernel reach the sidewall of the tube. From this time on, the two detonation fronts further propagate in opposite directions, consuming the combustible material along their way to the tube ends. At 229 μs, reflected shocks from the sidewall can be observed, which raise the pressure above 100 bars again. The overall gas density and concentration of each species including water increase accordingly. These reflected shocks can serve as additional initiation source at marginal conditions where the original annular-jet-induced cylindrically imploding shock is not strong enough to initiate detonation directly. After 229 μs, the both detonation fronts have been fully established and travel at a slightly overdriven condition in their respective directions.

Jet Parameters Required for Initiation

The simulation shown in Fig. 2 clearly indicates that detonation can be initiated by imploding shocks generated by an annular jet at quite modest conditions, for example, jet pressure of 2.0 bars and jet temperature of 250 K. This jet pressure and temperature correspond to a total pressure less than 5 bars and a total temperature of about 300 K, which are well within practical engineering reach.

In addition to the simulation shown in Fig. 2, we have conducted a series of simulations to systematically explore the initiation effectiveness of this concept at different jet and geometric conditions. For the same tube and jet geometry, with the jet temperature the same, the minimum jet pressure needed for successful initiation by the imploding shock is 1.7 bars. At a jet pressure of 1.6 bars, the annular-jet-induced cylindrically imploding shock itself is no longer capable of directly initiating a detonation. However, the shock reflected from the sidewall evolves into a detonation front. In this case, it takes the combined effect of the original imploding shock and the sidewall-reflected shock to initiate a detonation. If the jet temperature is raised to 300 K (corresponding to the total temperature about 360 K), the minimum jet pressure for initiation becomes 1.3 bars. It the jet temperature is further increased to 400 K (corresponding to the total temperature of 470 K), the minimum jet pressure for initiation is 1.1 bars.

Compared to the cases studied in Ref. 2, where the three alternating air-fuel-air jets with a similar total width were used, the minimum required pressure for detonation initiation is significantly lower, 1.4 vs 2.2 bars at the jet temperature of 300 K and 1.6 vs 2.5 bars at the jet temperature of 250 K. The relatively poor performance of the alternating jets reported earlier was mainly because the jets were angled towards the endwall for enhancing mixing among the jet materials, resulting in less momentum vertical to the tube wall, and, hence, a weaker imploding shock. This also implies that the effect of combustion among jet materials and between jet materials and the combustible mixture already in the tube is far less important than that of the imploding shock generated by the jet momentum.

Numerical simulations were also conducted to study the effect of the jet width and location. For the jet width of 1.125 cm, the minimum required pressure for detonation initiation is about 3.1 bars for jet temperature of 250 K and 2.7 bars for jet temperature of 300 K. The simulations also show that the jet location along the tube has a very minor effect on the jet condition needed for detonation initiation.

Conclusions

We have explored the concept of initiating detonations using annular-jet-induced cylindrically imploding shocks for pulse detonation engine and other detonation-based applications. Our numerical simulation have shown that detonation can be initiated by a single, monocomponent annular jet at modest jet pressures and temperatures that can be readily provided by practical engineering means. The jet material can be the same fuel used in the engine or air, which is particular beneficial for airbreathing applications. Application of this jet initiation concept also eliminates necessity of using electric spark or laser ignition systems, significantly simplifying the engine design. However, there are significant model and numerical uncertainties in the simulations. Hence, further experimental and numerical studies are needed to further verify and quantify this initiation concept and refine it for practical engine applications.

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References

[1]Smirnov, N. N., Nikitin, V. F., Boichenko, A. P., Tyurnikov, M. V., and Baskakov, V. V., "Deflagration to Detonation Transition in Gases and Its Application to Pulsed Detonation Devices," *Gaseous and Heterogeneous Detonations*, edited by G. Roy, S. Frolov, K. Kailasanath, and N. Smirnov, ENAS Publishers, Moscow, 1999, pp. 65–94.

[2]Li, C., and Kailasanath, K., "Detonation Initiation in Pulse Detonation Engines," AIAA Paper 2003-1170, Jan. 2003.

[3]Kailasanath, K., "Recent Developments in the Research on Pulse Detonation Engines," *AIAA Journal*, Vol. 38, 2003, pp. 1698–1708.

[4]Brophy, C., Sinibaldi, J., and Damphousse, P., "Initiator Performance for Liquid-Fueled Pulse Detonation Engines," AIAA Paper 2002-0472, Jan. 2002.

[5]Lieberman, D. H., Parkin, K. L., and Shepherd, J. E., "Detonation Initiation by a Hot Turbulent Jet for Use in Pulse Detonation Engines," AIAA Paper 2002-3909, July 2002.

[6]Knystautas, R., Lee, J. H., Moen, I., and Wagner, H. G. G., "Direct Initiation of Spherical Detonation by a Hot Turbulent Gas Jet," *Proceedings of the Combustion Institute*, Vol. 17, 1979, pp. 1235–1245.

[7]Moen, I. O., Bjerketvedt, D., Jenssen, A., and Thibault, P. A., "Transition to Detonation in Large Fuel-Air Cloud," *Combustion and Flame*, Vol. 61, No. 2, 1985, pp. 285–294.

[8]Carnasciali, F., Lee, J. H. S., Knystautas, R., and Fineschi, F., "Turbulent Jet Initiation of Detonation," *Combustion and Flame*, Vol. 84, No. 1, 1991, pp. 170–182.

[9]Dorofeev, S. B., Bezmelnitsin, A. V., Sidorov, V. P., Yankin, J. G., and Matsukov, I. D., "Turbulent Jet Initiation of Detonation in Hydrogen-Air Mixtures," *Shock Waves*, Vol. 6, No. 1, 1996, pp. 73–78.

[10]Levin, V. A., Nechaev, J. N., and Tarasov, A. I., "A New Approach to Organizing Operation Cycles in Pulse Detonation Engines," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM, Moscow, 2001, pp. 223–238.

[11]Achasov, O. V., and Penyazkov, O. G., "Some Gasdynamic Methods for Control of Detonation Initiation and Propagation," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM, Moscow, 2001, pp. 31–44.

[12]Jackson, S. I., and Shepherd, J. E., "Initiation Systems for Pulse Detonation Engines," AIAA Paper 2002-3627, July 2002.

[13]Li, C., Kailasanath, K., and Oran, E. S., "Detonation Structure Behind Oblique Shocks," *Physics of Fluids*, Vol. 6, No. 4, 1994, pp. 1600–1611.

[14]Babushok, V. I., and Dakdancha, A. N., "Globe Kinetic Parameters for High-Temperature Gas-Phase Reactions," *Combustion, Explosion and Shock Waves*, Vol. 29, No. 2, 1993, pp. 289–303.

[15]Boris, J. P., and Book, D. L., "Flux-Corrected Transport I: SHASTA, A Fluid Transport Algorithm that Works," *Journal of Computational Physics*, Vol. 11, No. 4, 1973, pp. 38–47.

[16]Landsberg, A. M., Young, T. R., and Boris, J. P., "An Efficient, Parallel Method for Solving Flows in Complex Three-Dimensional Geometries," AIAA Paper 94-0413, Jan. 1994.

[17]Li, C., Kailasanath, K., and Patnaik, G., "A Numerical Study of Flow Field Evolution in Pulse Detonation Engines," AIAA Paper 2000-0314, Jan. 2000.

[18]Li, C., and Kailasanath, K., "A Numerical Study of Reactive Flows in Pulse Detonation Engines," AIAA Paper 2001-3922, July 2001.

[19]Li, C., and Kailasanath, K., "Performance Analysis of Pulse Detonation Engines with Partial Fuel Filing," *Journal of Propulsion and Power*, Vol. 19, No. 5, 2003, pp. 908–916.