# Study of fuel-oxygen mixing in a rotating detonation engine cold analog

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## 1 Introduction

Traditionally, most propulsion and combustion-based energy generation systems use isobaric combustion (deflagration) to convert the chemical energy into usable work. Significant research has been carried out to develop detonation-based combustors because of the possibility of increased thermal efficiency. The first investigation of a "spinning detonation" in a fixed position was by Voitsekhovskii et al. [1]. Nicholls and Cullen [2] found that the Voitsekhovskii concept of a rotating detonation wave propulsion system was conceptually viable, the limited understanding of detonation waves and the difficulty of using separate injection of fuel and oxidizer prevented the study from producing a viable prototype. In recent years, many research groups have constructed Rotating Detonation Engine (RDE) prototypes to investigate the effect of fuel and oxidizer injector configuration and combustion chamber parameters on the cycle frequency and detonation wave structure [3]. Typically, the detonation front is tracked via pressure transducers arranged around the circumference, or OH chemiluminescence imaging through the open exhaust-end [2], or through a Pyrex sidewall [4].

The use of schlieren photography is not possible for an annular RDE because it relies on collimated light transmission. A linear (unwrapped) RDE has two flat window surfaces conducive to schlieren photography; where a single pass of the detonation through the layer is visualized after an initial combustion event generates a combustion products atmosphere [5]. A single-shot linear RDE cold analog was used to obtain simultaneous schlieren video and detonation cell structure [6]. Premixed hydrogen-oxygen was injected through an array of holes into argon preloaded into a 7 mm wide channel. Although the burning at the interface of the fresh loaded gas in a RDE is not reproduced, this setup allows one to vary the properties of the product gas simulant, and most importantly, capture the cell structure that reveals the impact of the injected fuel-oxygen mixing with the inert gas on the detonation wave. Three-dimensional calculations show that there is significant "un-mixedness" of the fuel and oxygen in the region near the injection-plate [7]. In this study, the setup used in [6] was modified to allow the separate injection of fuel and oxygen into the channel, schlieren video and soot foils were used to characterize detonation propagation.

## 2 Experimental

The apparatus is comprised of six 0.61 m long sections, the first four sections are used to generate a detonation wave via flame acceleration and deflagration-to-detonation transition (DDT). A flame is ignited by a standard coil-over-plug automotive ignition system located at the endplate. Fence-type obstacles at the ignition end, mounted on the top and bottom walls equally spaced at 76 mm, are used to promote flame acceleration. The obstacle blockage ratio used in the first three channel sections are 66%, 50%, 33%, respectively. The detonation wave stabilizes in the obstacle-free fourth section before entering the optically accessible test-section. Four ion probes mounted on the top wall of the third and fourth sections, equally spaced 0.3 m, provide combustion front time-of-arrival data used to obtain the combustion front velocity. The test-section is isolated from the predetonator (first four sections) by a manually operated sliding door that has an aperture similar to the channel inner cross-section of 63.5 mm by 12.7 mm. The predetonator is filled with premixed hydrogen/oxygen and the test section and dump tank are initially filled with argon to 1 atmosphere. The sliding door is opened, activating a micro-switch that triggers the DAQ system. A 5V output signal from the DAQ closes a solid-state relay that powers the hydrogen and oxygen solenoid valves. High-speed video of the energized solenoid separated from the valve showed that the valve stem starts to move after 6 ms, and is fully open after 15 ms. The DAQ 5V output signal also goes to a delay generator whose pre-set delayed 5V output signal activates the ignition system. This delay time is the main parameter in the experiment, and in effect governs how long the hydrogen/oxygen flows into the channel before the detonation arrives at the test-section. A typical delay time was 19-21 ms, based on the detonation time-of-arrival at the manifold pressure transducer from the time the door switch closed.

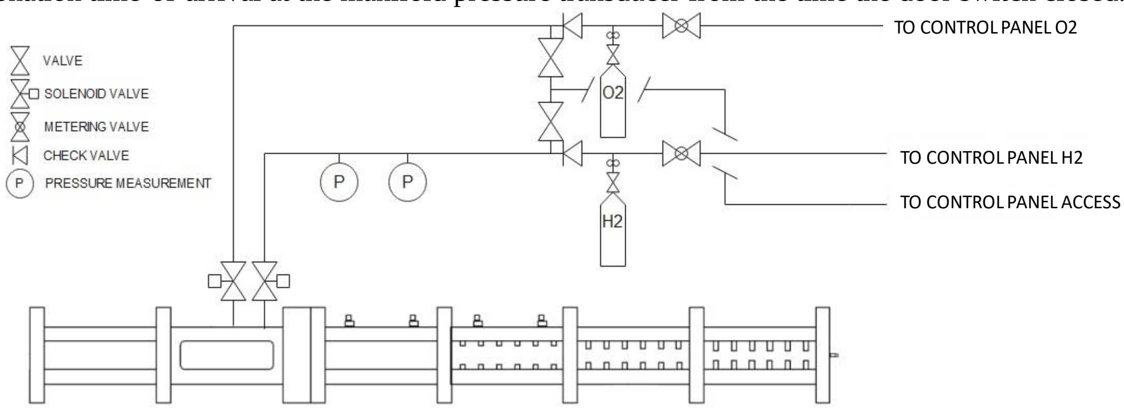


Figure 1 Schematic showing the test channel and fuel oxygen delivery piping

A schematic of the gas injection piping from the gas cylinders is shown in Fig. 1. The fuel and oxygen were preloaded into 1.6 m long, 10.8 mm internal-diameter rigid stainless steel tubing between the solenoid valve and the check valve located after the compressed gas cylinder. The 12 VDC solenoid valves (with 4 mm orifice) were located roughly 145 mm above the manifold inlet. Downstream of the solenoid valves, all of the piping and plenum is initially filled with argon; it is important to minimize this volume to reduce the amount of inert gas that would need to be displaced by the injected gas. A 38 mm instrument plug with two 3.2 mm (1/8”) holes fed the manifold that was mounted to the top of the test-section. A schematic showing the flow path in the instrument plug, and photo of the solenoid valves mounted onto the plug are provided in Fig. 2. The plenum assembly consisted of two plates bolted together with a BUNA-N gasket sandwiched between them. Two side-by-side 438 mm long, 3.2 mm x 3.2 mm cavities were machined into the bottom plenum plate that received the gas through 3.8 mm holes in the top plate. The gas from the plenum cavities discharge into the channel through a series of ninety-four 1.3 mm diameter holes (No. 55 drill size, 10.9 mm long), axially-spaced 4.8 mm center-to-center. The fuel and oxygen jets impinged at an angle of 30° off the vertical, the paired holes were 3.3 mm apart (center-to-center) at the bottom face of the plenum assembly.

The oxygen bottle regulator was set to 725 kPa (all pressures in this section are gauge), dictated by the solenoid valve maximum operating pressure. The hydrogen bottle regulator was varied between 100 kPa and 400 kPa to change the mixture composition. Once the solenoid valve closed, the pressure in the feed line after the check valve reached a pressure lower than the regulator pressure. For oxygen, this pressure was 655 kPa, and for hydrogen a regulator pressure of 400 kPa and 200 kPa resulted in feed line pressure of 330 kPa and 150 kPa, respectively. To achieve a stoichiometric mixture, the oxygen to hydrogen pressure needed to be 2:1, corresponding to a hydrogen regulator pressure of 400 kPa.

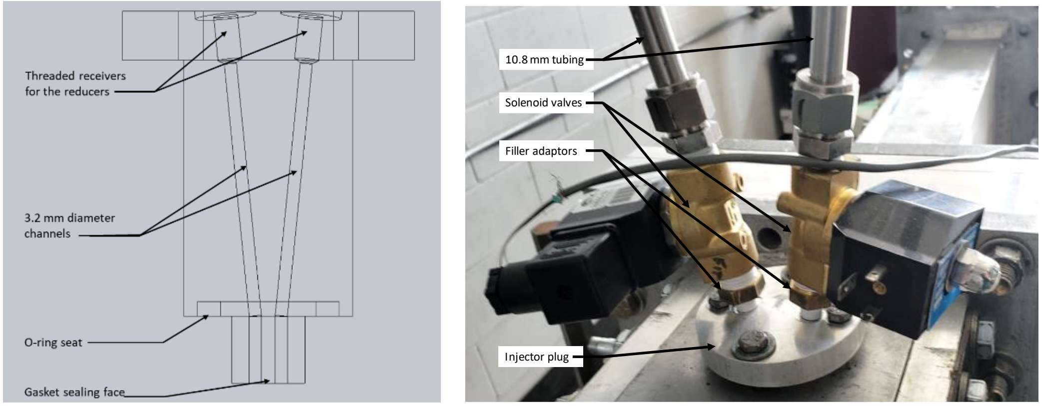


Figure 2 Schematic of instrument plug (left), photo of solenoids and top of instrument plug (right)

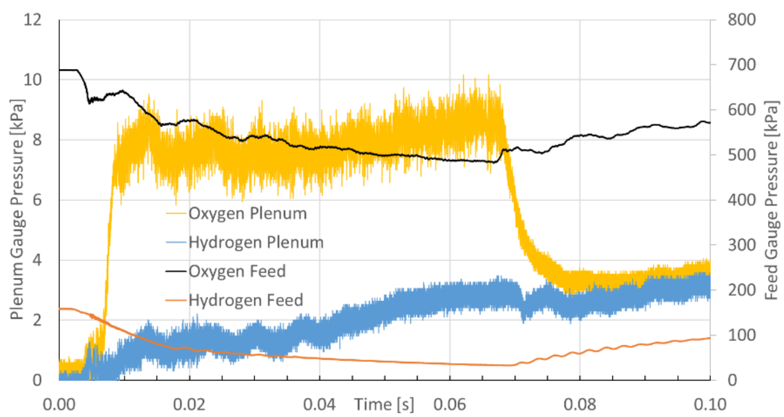


Figure 3 Pressure traces recorded for the injection of hydrogen (200 kPa regulator pressure) and oxygen (725 kPa regulator pressure) into argon. The PT was located 343 mm from the plenum inlet. (Test 849)

To characterize the hydrogen and oxygen flow to the plenum, and to aid in CFD modelling of the layer development, piezoelectric pressure transducers were placed in the plenum and in one of the feed lines just before the solenoid valve (see Fig. 1). The detonation reaches the test-section after about 20 ms, after this time the flow through the valve is of no consequence to the experiment. The pressure recorded in the oxygen feed line, located 300 mm before the solenoid valve, shows a sudden drop after about 4-5 ms, see Fig. 3. This delay is slightly shorter than the 6 ms the video showed the valve stem starts moving under no pressure. It takes 0.9 ms for the head of the expansion fan to reach the pressure transducer. The pressure drops from 690 kPa to 500 kPa, after the solenoid valve starts closing at 60 ms the pressure rises. The pressure in the manifold starts rising at roughly 4.5 ms, a rapid pressure rise to a quasi-steady value of 8 kPa occurs at 7 ms until the valve closes. For the hydrogen, the feed line pressure starts to drop mildly at 3 ms from 156 kPa to 70 kPa at 20 ms, and the manifold pressure reaches a value of under 2 kPa. The magnitude of both the hydrogen and oxygen plenum pressure indicates that the flow from the plenum into the channel is not choked; the flow chokes in the 3.2 mm plug passage between the solenoid valve and the manifold. Moving the pressure transducer upstream to 114 mm from the plenum inlet produced a maximum pressure of 20 kPa and 28 kPa for the hydrogen and oxygen, respectively. Since the hydrogen and oxygen pressure drops over the length of the plenum, a decreasing mass flow rate is expected down the length of the plenum.

## 2 Results and Discussion

Schlieren images showing the detonation propagation at the end of the layer are provided in Fig. 4. In the first two images, the detonation enters the field-of-view (FOV) fully coupled, except for the very bottom where there is decoupling into a shock and reaction front. Transverse striations associated with the transverse waves (off the triple-points and into the products) are observed. In the third image, most of the detonation is decoupled, except at the top where a detonation kernel forms, highlighted by an arrow. Detonation propagation through the rest of the layer is characterized by an unsteady "chugging" along the top of the channel while the rest of the front is decoupled. The detonation propagates forward and downward from the hot spot that forms at the top wall in image 3. The downward detonation propagation is limited by the bottom edge of the layer, where it decouples, generating an inert shock and trailing contact surface between the compressed argon and products. Starting from Fig. 4 image 7, the reaction front takes on a saw tooth pattern generated from successive detonation re-initiations.

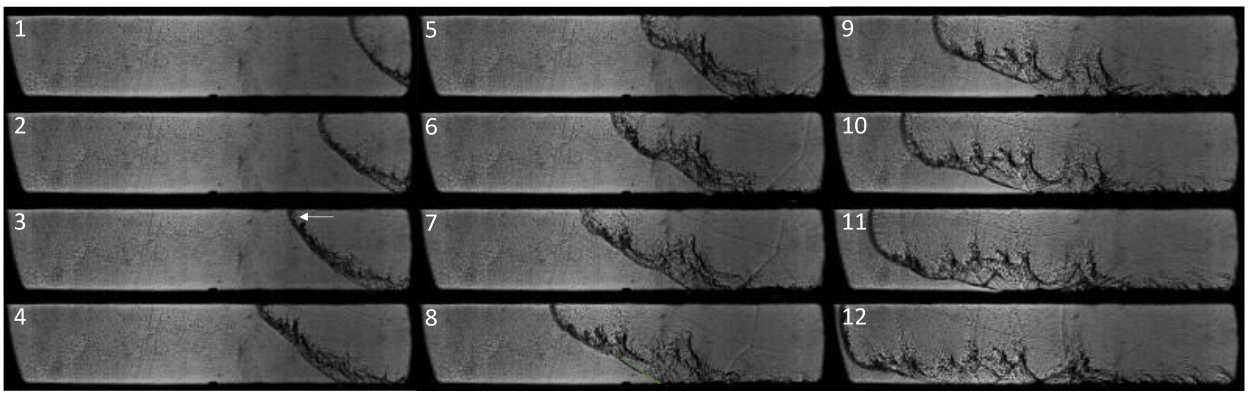


Figure 4 Propagation of a detonation through the end of the layer with 21.5 ms of delay. Hydrogen regulator pressure 200 kPa (Test 641 with argon). Frames are equally spaced 8.3 μs apart.

The location of the detonation front along the top wall was tracked; the average detonation velocity between video frames is plotted in Fig. 5. The detonation propagated across the FOV with an average velocity of 1725 m/s, roughly 1000 m/s below the CJ detonation velocity for stoichiometric hydrogen-oxygen. The velocity deficit is due to the mixing of the hydrogen and oxygen and dilution with argon. Frictional losses are believed to be minimal as there are 10 cells across. The average velocity drops towards the end of the layer, which could be due to the reduced layer height, and associated reduced mixing time.

Both side windows were coated with soot to simultaneously capture the cell structure and the detonation front luminescence on video. Note, the hydrogen flowed into the camera-side plenum, and the light-source-side piping fed the oxygen jets. Because the holes were drilled at a 30-degree angle to the vertical, the hydrogen jets angled towards the window on the light-source-side, and the oxygen jets angled towards the window on the camera side. The bottom soot imprint in Fig. 6, obtained on the light-source-side of the channel shows very little cell structure except for at the beginning. The top soot imprint, obtained on the camera-side of the channel, where the stronger oxygen jet produces a wall jet (discussed later), features a cellular structure that corresponds to detonation propagation over the entire length of the jet layer.

The first 15 cm of the foil (6 inches on the scale) consists of relatively uniform small cells. The detonation then forms a series of patches containing small cells. Initially, only a single strong triple-point starts from the top wall, whereas in the second half of the foil, the cell containing patch border takes on the shape of a chevron ">", see dotted lines in Fig. 6. The chevron lines correspond to two strong triple-points propagating in opposite directions on the detonation front. This patched cellular structure is characteristic of a detonation "burst", i.e., initiation at a point followed by propagation and failure. The average cell size within the different detonation bursts correspond to the local condition of the layer, e.g., at the end of the foil, the cell size within the chevron is larger indicating a more argon diluted mixture. There is evidence of strong triple point trajectories on the opposite foil, however these do not line up with those on the light-source-side, a strong indication that the detonation initiates at a point on the light-source-side window. The lack of fine cells on the camera side means that there is very little to no combustible mixture next to that window. High-speed video, overlaid onto the foil in Fig. 7, shows the luminescence correlates with the recorded cellular structure, with each reinitiation producing an acceleration of the wave front at the start of each patch of cells.

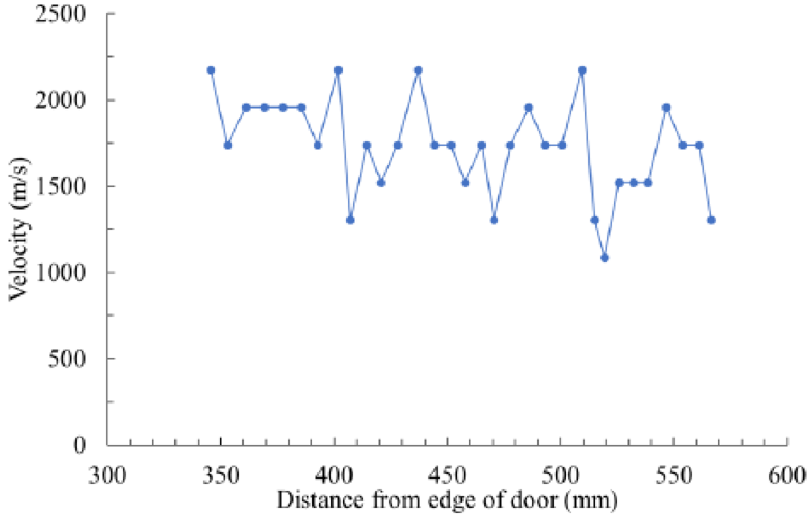


Figure 5 Detonation velocity vs position for a test with 19.5 s delay and hydrogen pressure of 200 kPa (Test 841)

The extent of detonation propagation, quantified by the percentage of the FOV (at the end of the layer), for a wide range of hydrogen regulator pressures and jet delays is provided in Fig. 8. Detonation propagation through the entire FOV occurred for the highest hydrogen regulator pressure and longest delay times, i.e., top right corner of map. The results indicate that the layer produced by a hydrogen supply pressure of 200 kPa is conducive to detonation propagation, resulting in propagation through the entire FOV for a large range of delays. Increased delay leads to a larger mass of hydrogen-oxygen mixture injected, producing a thicker layer. The larger delay also gives more time for the hydrogen and oxygen to mix. An increased hydrogen supply pressure, for fixed delay, leads to a thicker layer and more mixing time since the hydrogen reaches the end of the plenum faster. A delay of 18.5-19.5 ms was the minimum amount of time required for the layer to develop and sustain the detonation, with a minimum pressure of 150-200 kPa required for the hydrogen supply.

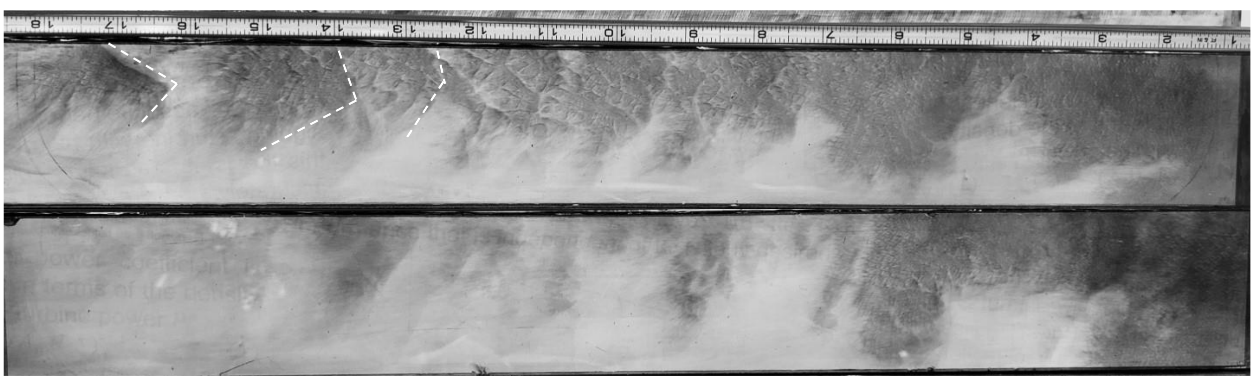

Figure 6: Window soot impressions. Top foil is the camera-side window that the oxygen jet was directed towards. Hydrogen pressure of 200 kPa and delay of 21.5 ms. Scale in inches. (Test 932)

Three-dimensional, laminar, ANSYS Fluent simulations were conducted of the entire gas delivery and channel to predict the mixing in the channel. The plenums were resolved with 13 mesh point across; the top 5 mm and middle of the channel, where the layer develops, had 23 and 14 mesh points, respectively. The simulation show that at the end of the channel the higher momentum oxygen jet started earlier than the hydrogen, and the interaction of the two jets produced a mixed-gas wall jet on the camera-side of the channel, see Fig. 9. Sato et al.'s calculations showed a similar asymmetry in the transient recovery of hydrogen and air jets in a RDE after the passage of the detonation wave [7]. They also showed that the transient jets produce pockets of high and low equivalence ratio.

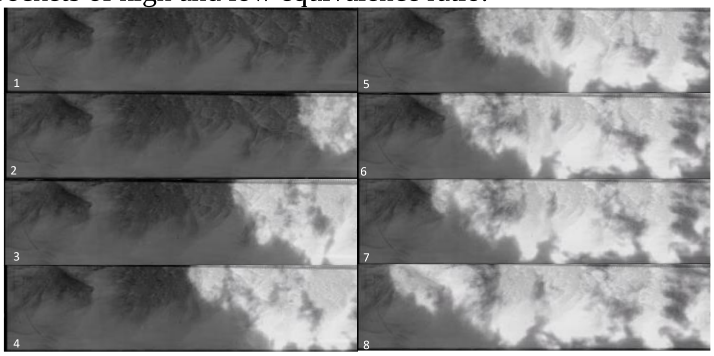


Figure 7 Overlay of the luminescence overlaid onto the cellular structure recorded on the camera side window. Same test as Fig. 6.

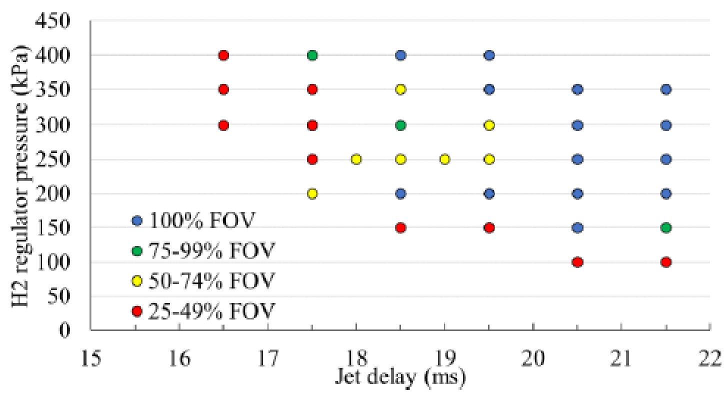


Figure 8 Effect of hydrogen pressure and ignition delay on detonation propagation through FOV

## Conclusions

An experimental setup to study mixing and detonation propagation in a non-premixed injection RDE geometry was developed. Stereo soot impressions were used to show asymmetric mixing for a hydrogen-oxygen system with 30º inclined injection holes. Future testing will include the use of ethylene in place of hydrogen to better match the jet densities, and a narrower channel width to promote mixing of the fuel and oxidizer and to improve the scavenging of the argon.

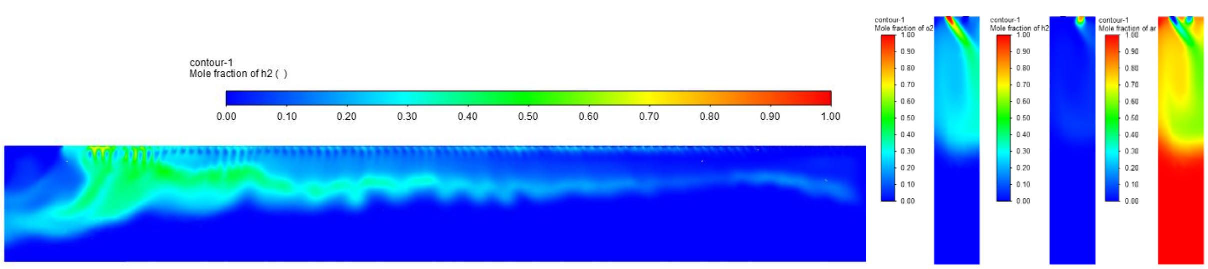


Figure 9 CFD predictions at 19 ms delay (assuming 6 ms for valve opening), a) hydrogen mole fraction along the axial mid plane, b) oxygen, hydrogen, argon cross-section mole fraction at the end of the layer.

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