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Tailored Fuel Injection for Pulsed Detonation Engines via Feedback Control

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An architecture is developed for feedback regulation of liquid volume fraction profiles in an air jet confined in a tube. The application to the controlled injection of fuel in detonation tubes for pulsed detonation engines is considered. The architecture consists of laser attenuation sensing of liquid volume fraction along the tube, actuation on the liquid injection pressure through an array of solenoidal valves, and proportional–integral feedback. The architecture is validated by means of cold-flow experiments regulating the concentration profile of water droplets along the detonation tube to desired values.

I. Introduction

PULSED detonation engines (PDEs)[1–3] produce thrust by successive detonations of a fuel–oxidizer mixture in a tube. They have two main advantages over other means of propulsion. The first is of thermodynamic efficiency; detonation is the closest approximation to the constant volume heat release in the Carnot cycle. Chapman–Jouget theory shows that the detonation pressure is the maximum pressure attainable by a self-sustaining compression–combustion wave. The second is simplicity of construction and consequent reliability; the engine comprises only a set of detonation tubes, with no need for compressors or turbines. Past projects attempting to construct PDEs were hobbled by the inability to maintain the conditions necessary for detonation. The difficulties were twofold: a lack of understanding of the process of detonation and the inability to sustain detonation over a wide range of operating conditions. Research efforts over the past four decades, first in experiments and then in numerical simulation, have brought to light the complex mechanisms governing the phenomenon. (See Ref. 4 and references therein.) This understanding, combined with advances in high bandwidth sensing and actuation and in control theory, has induced a renewed interest in the development of PDEs.[5]

It is now widely accepted that sustaining detonations in the face of changing operating conditions (air density, temperature, and pressure variations due to changes in Mach number, 0.5–5, and altitude, 0–15,000 m) during flight calls for feedback control that can adapt to these changing conditions. In an effort to maximize thrust produced by PDEs, the objective of maintaining detonation conditions must be first met. Tailoring the injection process so that an optimal equivalence-ratio profile is obtained along the axis of the detonation tube can significantly enhance the detonability of the mixture, thus, preserving the conditions required for the successful operation of the engine. This strategy requires feedback regulation of the fuel-flow rate to maintain equivalence-ratio profiles conducive to detonation along the tube via measurement and actuation of appropriate quantities through a control algorithm.

It has been shown by previous studies[6–8] that a high-momentum gaseous jet can be used to atomize a liquid stream and that the characteristics of the resulting spray are determined by the mass, momentum, and swirl ratios between the liquid and gas streams. This phenomenon can be applied to the design of the injection system for a PDE. The high-momentum airstream coming from the aerodynamic inlet is injected into the tube coaxially with the fuel jet. The fuel is, thus, atomized and convected downstream, mixing with the oxidizer and filling the tube. When appropriate values of the mass, momentum, and swirl parameters of the jets are selected, the tube can be filled with a radially uniform spray of very small droplets ($d_{10} \approx 10\ \mu$m), so that a detonation can propagate through the mixture. Furthermore, by pulsating the pressure of fuel injection, the axial fuel distribution can be altered, so that an optimal injection law can be implemented under changing operating conditions.

We present in this paper the development of a control architecture that can be applied to the fuel injection of PDEs: sensing of equivalence ratios along the detonation tube by laser attenuation measurements, actuation of fuel flow through an array of solenoidal on–off valves, and regulation of the equivalence ratio profiles through a proportional–integral control law. We also present results of water–air experiments on this setup that demonstrate the capability to regulate liquid volume fraction profiles along a tube to commanded values.

The outline of the paper is as follows: In Sec. II, the experimental setup, the calibration of the sensors, and the actuators are described. In Sec. III, the details of the control design are explained. The results from the experiments are shown in Sec. IV, whereas the conclusions extracted from this work are summarized in Sec. V.

II. Experimental Setup

The experimental set-up is shown in Fig. 1. The liquid and gaseous streams are injected by two coaxial jets with low and high momentum, respectively, discharging into the tube. The liquid jet is atomized by the gaseous turbulent jet, which produces a droplet spray of known characteristics, shown in Fig. 2. This breakup process occurs in a very small region of the tube, close to the injector. The spray is then convected downstream, disperses in the gas, and fills the rest of the tube.

The gas stream is injected continuously and enters the tube at a Mach number of approximately 0.5 and a Reynolds number of 10^5. The liquid jet, with a Reynolds number of 2×10^3, is injected intermittently, with the injection pressure determined by a set of eight solenoid valves. These valves are regulated by a proportional–integral control algorithm to achieve the desired liquid volume fraction profile along the tube. The control algorithm determines the opening and closing times of the valves, which, in turn, shapes the injection pressure waveform during the portion of the cycle allocated for injection, in this case 50 ms. The valves are closed during the rest of the cycle, allowing for the hypothetical ignition, propagation, and exhaust of a detonation wave.

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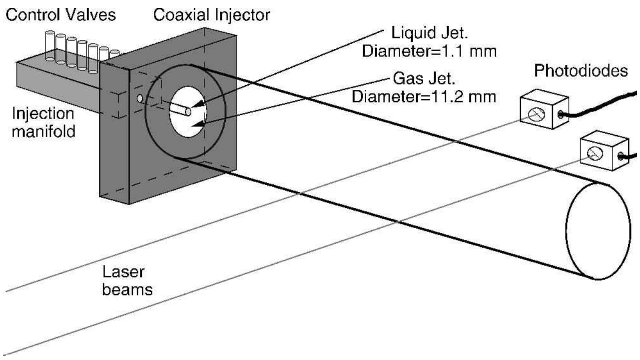


Fig. 1 Schematic of cold-flow experiment.

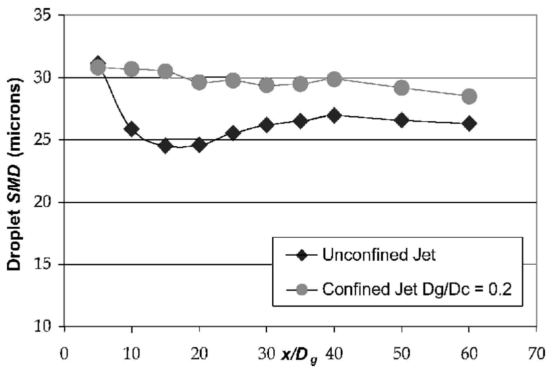


Fig. 2 Characteristics of the droplet size distribution; evolution of the Sauter mean diameter with distance downstream.

Photodetectors are located at different distances downstream along the tube. An array of parallel laser beams, coming from an Ar ion source, crosses the spray through the center plane of the tube and hits the photodetectors. The temporal and longitudinal distributions of liquid volume fraction along the tube are studied by measuring the attenuation due to the droplets of the laser light intensity at the location of the photodetectors. The output of the photodetectors at the instant that the valves close is used by the control algorithm to determine the liquid injection law during the next cycle.

The rise time of the photodetectors is negligible compared to the other components in the loop, 1 μs or less. The response time of the system is given by the combined responses of the acquisition and digitizing and of the actuators. A National Instrument acquisition card is used for acquisition and digitizing, and LabVIEW software is used to implement the control algorithm. These two elements have a joint response time of 1 ms. The electromechanical response time of the valves is also 1 ms. Thus, the combination of very fast sensors and actuators ensures that the response time of the whole feedback loop is much smaller than the time between the end of an injection cycle and the beginning of the next, which is of the order of 20 ms.

A photograph of the whole experimental setup is shown in Fig. 3. We can observe the plexiglass tube filled from the closed end by the water–air mixture. An array of laser beams crosses the tube at its centerline, and each beam is attenuated by the spray, which is being convected down the tube. The attenuation at each location is measured by a photodiode, which is hit by the beam after crossing the tube.

A. Sensing

The technique for measuring the concentration of water droplets at a particular cross section is based on Bouger's law (see Ref. 9). The attenuation by absorption and scattering of a laser beam of wavelength λ propagating along the r direction in a medium of thickness L is given by

$$\ell n \frac{I}{I_0} = -\int_{-R}^{R} \sigma_\lambda(r)\,\mathrm{d}r \tag{1}$$

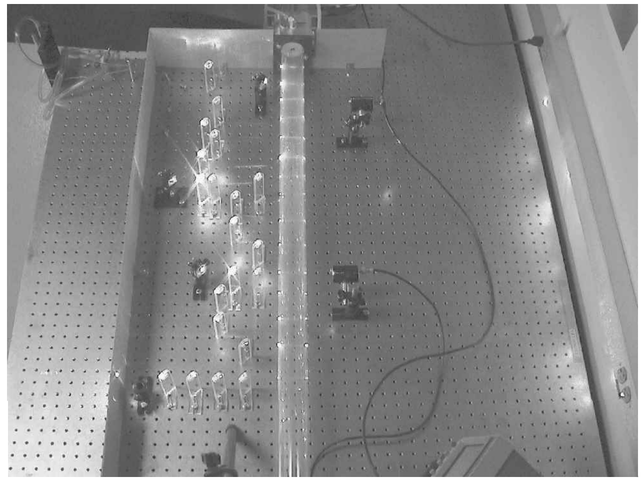


Fig. 3 Cold-flow experiment setup.

where $\sigma_\lambda(r)$ is the medium's scattering and absorption coefficient and R is the radius of the spray. When the scattering medium is composed of spherical particles and multiple scattering effects can be neglected, an analytical expression for $\sigma_\lambda(r)$ can be obtained as a function of the particle concentration and its optical properties:

$$\sigma_\lambda(r) = \frac{6\alpha_P(r)}{\pi}\int_0^\infty S_\lambda(D)\frac{f(D,r)}{D^3}\,\mathrm{d}D \tag{2}$$

where $\alpha_P(r)$ is the volume fraction of the dispersed phase at location r, $S_\lambda(D)$ is the optical cross section of a particle of diameter D, and $f(D,r)$ is the particle volume probability density function at location r. Note that the normalization condition is given by

$$\int_0^\infty f(D,r)\,\mathrm{d}D = 1$$

The optical cross section $S_\lambda(D)$ can be computed from Mie's theory (see Ref. 10), which gives a value of $\pi D^2/2$ for the conditions of our experiment. Using the definition

$$\bar{\alpha}_P \bar{f}(D) = \frac{1}{2R}\int_{-R}^{R} \alpha_P(r) f(D,r)\,\mathrm{d}r \tag{3}$$

we can express the mean concentration $\bar{\alpha}_P$ as

$$\bar{\alpha}_P = \frac{-\ell n(I/I_0)}{6R\int_0^\infty[\bar{f}(D)/D]\,\mathrm{d}D} \tag{4}$$

The volume fraction of liquid averaged along the beam's path is proportional to the logarithm of the ratio of light intensities with and without liquid spray. The proportionality constant, which is a function of the size distribution at each particular location downstream, is available from previous experimental research on confined and unconfined jets.[6] A more thorough description of this method to measure the volume fraction of a liquid spray in a gas stream may be found in Ref. 11.

B. Actuation

The liquid injection pressure, and thus the liquid flow rate, is regulated by eight on–off valves located at the back of the injector. These valves are opened or closed during certain intervals of the injection cycle by digital output signals provided by the feedback algorithm. To calibrate the liquid flow rate through the injector as a function of the number of valves open (injection pressure), the experiment was operated with each possible valve setting (1–8 valves opened) for a large number of cycles. The total liquid mass injected was collected from the tip of the injector and averaged over the total time of injection. The injection cycles were representative of the operating conditions of the experiments, which allow us to take into account the effect of the transients in the injected flow rates. (The valves were energized for 25 ms and closed for 25 ms.) The flow rate vs the number of open valves is illustrated in Fig. 4. The information contained in Fig. 4 was used by the feedback algorithm, in the form of a lookup table, to determine the number of valves to open during the next cycle in response to the concentration measurements in the present cycle.

III. Control Design

Note that, in a PDE, only the equivalence ratio profile $\alpha(z)$ at the end of the tube-filling process is of practical interest, and hence, only a snapshot of the sensor traces $[\alpha(z_1, T), \dots, \alpha(z_n, T)]$ at the valves closing time is used for the purpose of feedback control. Here, z is the longitudinal coordinate along the detonation tube, and T is the duration of the injection cycle.

The discrete nature of the actuation combined with the fast response time of the sensors $[\mathcal{O}(1\ \mu\text{s})]$ and actuators $[\mathcal{O}(1\ \text{ms})]$ justifies the use of the following discrete-time model relating actuation and sensing:

$$\boldsymbol{\alpha}_{k+1} = \boldsymbol{B}\boldsymbol{u}_k \tag{5}$$

where $\boldsymbol{\alpha}$ represents the liquid volume fraction measurements along the tube, $\boldsymbol{u}$ the injection pressure at each interval of the injection, and index k the kth cycle.

Our first control objective is to regulate the output $\boldsymbol{\alpha}$ to a given value $\boldsymbol{\alpha}^*$ using feedback control. This corresponds to regulating the input $\boldsymbol{u}$ to an unknown value $\boldsymbol{u}^*$, where $\boldsymbol{\alpha}^* = \boldsymbol{B}\boldsymbol{u}^*$, with the interaction matrix $\boldsymbol{B}$ being unknown. (The coefficients in $\boldsymbol{B}$ are very sensitive to variations in sensor positioning and ambient conditions.) We show how this can be done in the one-dimensional problem using a simple proportional–integral (PI) controller. First, we define error variables at the instant k:

$$\tilde{\alpha}_k = \alpha_k - \alpha^*, \qquad \tilde{u}_k = u_k - u^* \tag{6}$$

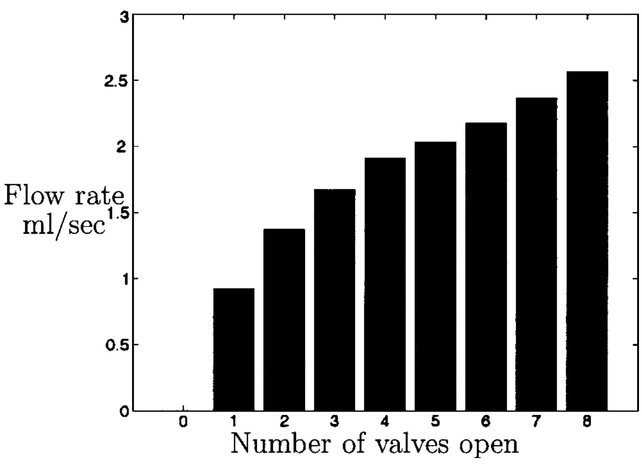


Fig. 4 Calibration of solenoidal valve array.

The goal of the control design can now be posed as regulating $\tilde{\alpha}_k$ and $\tilde{u}_k$ to zero. The PI control law in terms of $\tilde{\alpha}$ is

$$u_k = -g\tilde{\alpha}_k + v_k, \qquad v_k = v_{k-1} - h\tilde{\alpha}_{k-1} \tag{7}$$

where $g > 0$ is the proportional gain, $h > 0$ is the integral gain, and v is used to denote the integral part of the control. Denoting $\tilde{v}_k = v_k - u^*$, we rewrite the equations in terms of error variables,

$$\tilde{\alpha}_{k+2} = (1 - Bg)\tilde{\alpha}_{k+1} - B(h - g)\tilde{\alpha}_k \tag{8}$$

whose stability is assured if the roots of the polynomial $z^2 - (1 - Bg)z + B(h - g)$ lie within the unit circle on the complex plane. This can always be achieved by choosing $h = g$ and tuning g to achieve $|1 - Bg| < 1$. In that case, the closed-loop system has poles at 0 and $1 - Bg$, compared to 0 and 1 for the open-loop system. Hence, a small g will ensure the stability and convergence of α_k to the desired α^*, without knowledge of the matrix B.

The injection period can be divided into as many intervals as the speed of the actuators permits. There are two strategies to be explored: First, to choose the number of intervals equal to the number of sensors will result in a square $\boldsymbol{B}$ matrix. Moreover, this matrix will be diagonally dominant because the volume fraction at each cross section of the tube is mainly determined by the liquid flow rate at one particular instant of the injection (with the ratio between the distance and the time delay being the mean convection velocity of the spray). These two circumstances enable the use of a PI control which, neglecting the off-diagonal terms, reduces the problem to n one-dimensional stability tests such as the preceding one.

The second strategy could be to operate the experiment with a number of intervals smaller than the number of sensors. This would be the case when high spatial resolution in the volume fraction distribution is desired without a corresponding increase in the cost of the actuators. In this case the matrix $\boldsymbol{B}$ is rectangular and PI control cannot be used. In general a minimum distance problem would need to be solved,[12] to drive the sensor output as close to the desired value as possible. Adaptive stabilization[12,13] is necessary for this case where $\boldsymbol{B}$ is nondiagonal and high dimensional.

IV. Experimental Results

Figure 5 shows a cross-sectional schematic of the rig at the end of a fill-in process. The differential acceleration of droplets of different sizes that occurs during and immediately after the breakup process introduces a distribution of convective velocities in the spray. Thus, there is a certain coupling between all sensors and actuators, that is, nondiagonal terms in $\boldsymbol{B}$. In the two-input–two-output experiments, we design the control assuming a diagonal

$$\boldsymbol{B} = \begin{pmatrix} b_{11} & 0 \\ 0 & b_{22} \end{pmatrix} > 0$$

for stability of the following system:

$$\tilde{\alpha}_{k+2} = (\boldsymbol{I} - \boldsymbol{B}\boldsymbol{G}_P)\tilde{\alpha}_{k+1} - \boldsymbol{B}(\boldsymbol{G}_I - \boldsymbol{G}_P)\tilde{\alpha}_k \tag{9}$$

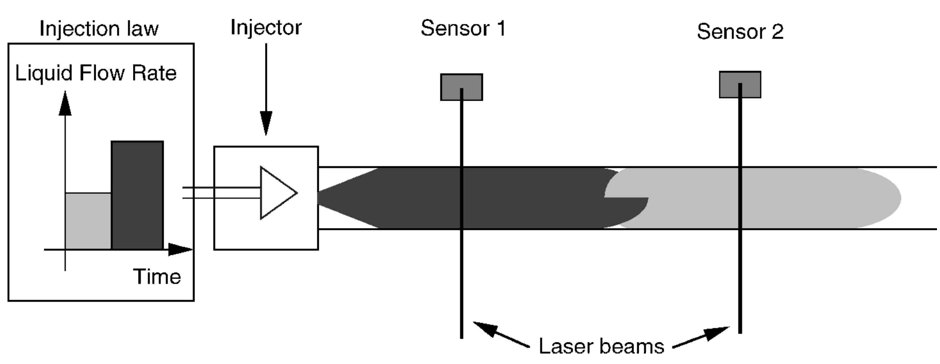


Fig. 5 Photodetector locations and spray distribution at the end of the injection cycle: two input–two output experiment.

where the proportional gain

$$\boldsymbol{G}_P = \begin{pmatrix} g_{11} & 0 \\ 0 & g_{22} \end{pmatrix}$$

and the integral gain

$$\mathbf{G}_I = \begin{pmatrix} h_{11} & 0 \\ 0 & h_{22} \end{pmatrix}$$

are diagonal and positive definite. In these experiments, $\boldsymbol{u}$ is a vector of dimension two, equal to the number of sensors, with a resolution of eight levels for each component. The filling time of 50 ms (which has been proposed for a PDE operating at 15 Hz per tube,[14] with the filling time taking up to 70% of the total period) is then divided into two 25-ms intervals, during which the injection pressure is determined by the number of open valves.

A. Turbulence and Digital Filter

Figure 6 shows the time evolution of raw and filtered sensor (photodiodes) outputs during an injection cycle. The fluctuations in the raw signals are significant, due to the turbulence fluctuations in the gas stream. We selected a third-order linear digital filter with poles at 45, 50, and 55 Hz for the purpose of obtaining averaged measurements of the liquid volume fraction. The delay associated with the filter is small (about 5 ms) and does not affect accuracy of our measurements for the purpose of actuation because it is much shorter than the delay between injection cycles (20 ms).

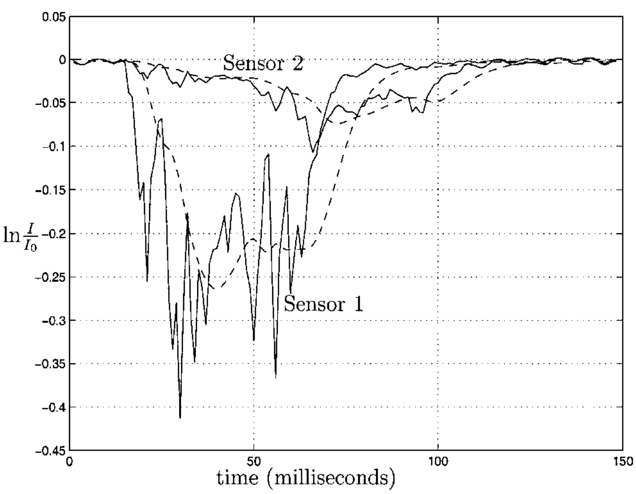


Fig. 6 Experimental sensor outputs during an injection cycle: ——, raw and – – –, filtered.

B. Real-Time Adaptation

A series of experiments was carried out in which the liquid volume fraction along the tube was driven to a predetermined desired distribution. Different initial conditions, as well as different desired distributions, were tested. The distributions chosen as goals were step-down distributions, where the water–air ratio is rich near the injector and lean toward the open end of the tube, with the overall ratio equal to stoichiometric for a typical hydrocarbon. This could be beneficial for sustaining detonations under changing conditions. This issue, the optimal fuel spatial distribution to sustain a detonation, is still an open question, and this type of distribution goal was chosen only as an example of the capabilities of the system.

It was found that the PI control was always able to regulate the liquid volume fraction to within a small error of the desired distribution in a few cycles. A typical history plot of an experiment is shown in Fig. 7. Here, n_1 and n_2 are the number of valves open in the first and second 25-ms intervals in the 50-ms injection period, and ε is the convergence criterion (the norm of the difference between the sensor output $\boldsymbol{\alpha}$ and the desired sensor output $\boldsymbol{\alpha}^*$).

C. Uniform Distribution

A particular case, one which is of special interest, is the problem of filling the tube with a uniform distribution along its axis. As already mentioned, fuel droplets are subject to strong acceleration when they are first subjected to the high-momentum gas stream, as well as strong deceleration as the gas expands and transitions between jet and pipe flows. Because aerodynamic forces are proportional to cross-sectional area and inertia is proportional to volume, droplets with different diameters have widely different convection velocities. Thus, uniform pressure at injection does not guarantee uniform fuel distribution. On the contrary, it guarantees a strongly nonuniform distribution of the equivalence ratio.

An experiment to demonstrate this phenomenon was done. Uniform initial conditions were used, and it was found that, indeed,

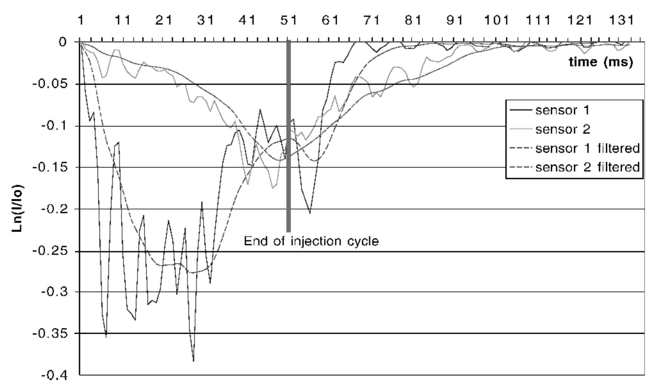
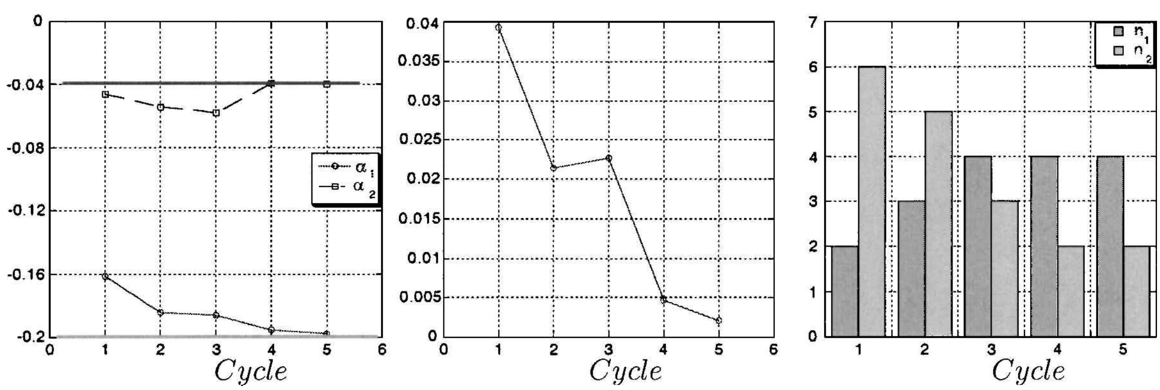


Fig. 8 Uniform liquid volume fraction distribution along the tube obtained by the control algorithm.



a) Attenuation **b)** $\varepsilon = \sqrt{[(\alpha_1 - \alpha_1^*)^2 + (\alpha_2 - \alpha_2^*)^2]}$ **c) Number of open valves**

Fig. 7 Feedback regulation of the liquid volume fraction profile.

uniform injection pressure in both intervals does not create a uniform distribution in the tube. When a uniform liquid distribution was set as the objective, the control algorithm was able to drive the system to the state where the attenuation measurements in both sensors at the end of the injection cycle were equal. The results are shown in Fig. 8.

V. Conclusions

We address the problem of injecting fuel in a detonation tube according to a predetermined optimal distribution to sustain detonations. A control strategy has been developed to use feedback control on the injectors to achieve the desired result. An experimental setup has been built to implement the control strategy under well-characterized conditions in a cold-flow atomization experiment.

Based on the analysis of the physical properties of our plant, a PI control law has been chosen as the best option in terms of simplicity and robustness. The PI algorithm has been implemented in the experimental rig and has been validated under different conditions.

Because the optimal fuel distribution is still an open question, different desired distributions were set as goals, and the system was always able to converge to those, starting from different initial conditions. This demonstrates the ability of a PI controller to regulate, in a few cycles, the volume fraction of fuel along the tube. This ability is important in the case of changing flight conditions such as gust winds or maneuvering, or changes in altitude (with corresponding changes in air density and pressure).

The particular case of obtaining a uniform droplet distribution along the tube has also been addressed. It has been shown that uniform injection pressure does not achieve a uniform longitudinal distribution. A uniform distribution was achieved by the feedback control by regulating the injection pressure so that it was higher at the beginning than at the end of the cycle.

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