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Porous Pressure-Sensitive Paint for Characterizing Unsteady Flowfields

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The fast response time characteristics of porous pressure-sensitive paint (porous PSP) are applied to unsteady flowfield measurements. The unsteady flowfield of a fluidic oscillator is investigated by using anodized aluminum (AA), thin-layer chromatography (TLC), and polymer/ceramic (PC) as porous supporting matrices. The frequency response of these PSPs is measured using a shock tube, showing responses of 12.2, 11.4, and 3.95 kHz for AA-PSP, TLC-PSP, and PC-PSP, respectively. Flow oscillations of various phases are captured with these porous PSPs in the fluidic oscillator tests, with AA-PSP giving the sharpest images.

Nomenclature

D	=	mass diffusivity of oxygen
l	=	thickness of a supporting matrix
P_{norm}	=	normalized pressure
t	=	time
τ	=	response time

Introduction

PRESSURE-SENSITIVE paint (PSP) measures surface pressure distributions by the processes of luminescence and oxygen quenching.[1] In the presence of oxygen in a test gas, the luminescent intensity of the paint is reduced by oxygen molecules from the gas, a process called oxygen quenching. Because the amount of oxygen in the test gas can be related to static pressures, one can obtain pressure signals from the change in the luminescent intensity of PSP. The advantage of this technique over conventional pressure tap and pressure transducer measurements is the ability to make global surface pressure measurements at a lower cost.

Porous PSP uses a porous material as a supporting matrix, which improves the oxygen diffusion process. Figure 1 schematically describes the difference between conventional polymer type PSP and porous PSP. For conventional PSP, oxygen molecules in a test gas need to permeate into the PSP layer for oxygen quenching. The process of oxygen permeation in a polymer layer produces slow response times for conventional PSP. On the other hand, the luminophore in porous PSP is opened to the test gas so that the oxygen diffusion process is faster than a conventional PSP. In general, porous PSP has excellent sensitivity in the low-pressure region and has a sensitivity equivalent to the polymer-based PSP at atmospheric conditions.

Fast responding PSP is necessary for measuring unsteady flowfields in rotating machinery, flutter tests, and short-duration wind tunnels. By the use of the fast response time characteristics of porous PSP, unsteady flowfields can be accurately measured. In this work, the response times of porous PSPs are characterized from measurements in a shock tube. A fluidic oscillator is chosen for study, which has an unsteady flowfield on the order of a few kilohertz, making it a good example for demonstrating the capabilities of porous PSP.

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Porous PSP Preparation

Throughout this work, three types of porous PSPs are used. Anodized aluminum (AA) PSP[2–4] uses AA as a porous supporting matrix. Thin-layer chromatography (TLC) PSP uses a commercial porous silica TLC plate as the matrix.[5] Polymer/ceramic (PC) PSP uses ceramic particles coated with a polymer.[6] Porous PSPs for this work use bathophen ruthenium as a luminophore. The AA is prepared according to the procedure developed by Sakaue et al.[4] The luminophore is dissolved in dichloromethane and the AA is dipped in the dichloromethane solution to apply the luminophore on the surface. TLC-PSP is prepared from a TLC plate (from Aldrich Chemical) with the luminophore molecules applied to the plate by dipping. PC-PSP is prepared based on the Scroggin et al. procedure.[6] The luminophore is dissolved in methanol, and the binder surface is dipped in the methanol solution to apply the luminophore.

Characterizing Response Time of Porous PSP

Response Time of PSP

There are two characteristic timescales that are related to the response time of the PSP. One is the luminescent lifetime of the luminophore and the other is the timescale of the oxygen diffusion process in the supporting matrix of the PSP. The luminescent lifetime ranges from a few nanoseconds to hundreds of microseconds, as shown in Table 1.[7,8] The response time of porous PSP cannot be made faster than the luminescent lifetime.

Table 2 shows the time response of a variety of pressure paints. Conventional PSPs have response times ranging from milliseconds to a few seconds, whereas porous PSPs have response times on the order of ten to a few hundred microseconds. As seen from Table 2, the PSP response time is usually much slower than the luminescent lifetime. Hence, the response time can be reduced by improving the diffusion process in the supporting matrix.

The response time of conventional PSP, τ, is given as[9,10]

$$\tau \propto l^2/D \tag{1}$$

where l is the thickness of the supporting matrix and D is the mass diffusivity of oxygen in the matrix. Based on this relationship, three approaches have been used to improve the response time of PSP. Two of them are applied to a conventional PSP, which uses a polymer as a supporting matrix. One of the approaches is to develop a PSP with the luminophore concentrated on the top of a matrix surface. This was accomplished by Carroll et al.[9] who reported a response time of 45 ms with a matrix thickness of 19 μm. Another approach is to reduce the thickness of the matrix. Hubner et al.[11] used this approach and reported response times of 3–6 ms with a thickness of 4–5 μm.

The third approach is to develop a PSP with high mass diffusivity by using a porous material as a supporting matrix. Baron et al.[5] used a commercial porous silica TLC plate as a matrix and reported that submillisecond response times can be obtained. Because a theoretical model that describes the response time of porous PSP has not been developed, the response time of porous PSPs must be directly measured.

Response Time Calibration Method

It is important to verify that the response time of porous PSPs is fast enough for unsteady flow measurements. There are two methods available to measure the PSP response time. One is to use a periodic pressure change, and the other is to use a step change of pressure. The method of using a periodic pressure change characterizes the response time from the phase shift of a porous PSP response from a periodic pressure. Jordan et al.[12] used an unsteady speaker for creating periodic pressures. The response limitation of this method is on the order of tens of microseconds. The other method characterizes the response time from the rise time of porous PSP signal following a step change of pressure. Solenoid valve switching typically has been used to create a step change in pressure for response time measurement.[2,5,9,13–15] Normally, this type of apparatus has a pressure rise time on the order of a millisecond and has a ringing noise because of its natural frequency. This method of creating a pressure change for PSP response time calibration is not fast enough for porous PSP. Therefore, a method of using a shock tube[11,16,17] is applied to measure fast response times. A step change of pressure is created by a normal shock wave in the shock tube. The pressure rise time of a shock tube is on the order of a few microseconds.

Figure 2 shows a schematic of the shock tube setup. The cross section of the shock tube is 55 mm by 40 mm rectangular, with a driver section length of 428 mm and a driven section length of 485 mm. An aluminum foil diaphragm separating the driver section from the driven section is burst by the pressure difference between two sections, with the driver pressure being 1 atm. The pressure difference creates a normal shock wave that travels toward the driven section. A reference pressure transducer and porous PSP are mounted on the sidewall so that a step change of pressure is observed when the normal shock wave passes. A pressure transducer from PCB Piezotronics (Model 103A11) is mounted flush with the shock tube wall. The transducer has a natural frequency of 13 kHz. The unsteady pressure signal from the transducer is used as a reference to convert the luminescent signal to pressure. Absolute pressure is measured by an Omega pressure transducer, which is connected to

Table 1 Luminescent lifetimes of luminophores used for temperature-sensitive paints (TSPs) and PSPs at room conditions

Luminophore	Lifetime, μs	Type	Reference
EuTTA	500	TSP	7
Perylene	0.005	TSP	8
Rhodamine B	0.004	TSP	7
Ru(bpy)	5	TSP/PSP	7
Perylene dibutylate	0.013	PSP	7
PtTFPP	50	PSP	7
PtOEP	50	PSP	7
Ru(dpp)	4.7	PSP	7

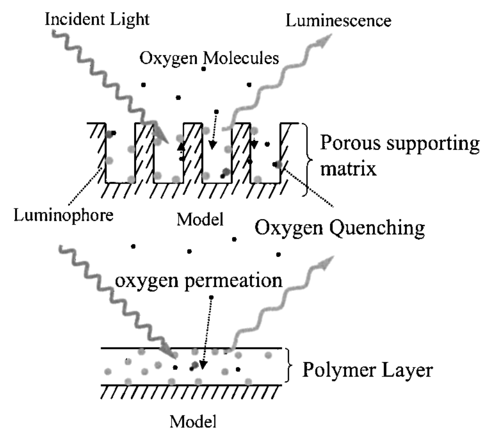

Fig. 1 Comparison of porous PSP and polymer (conventional) PSP.

Table 2 List of response times of PSP

PSP	PSP type	Thickness, μm	Decay time,[a] μs	Response time	Comment	Reference
LPSF1 (pyrene)	Conventional	2	NA	5 ms	OPTROD, Russia, formulation	16
PSPL2 (pyrene)	Conventional	20	NA	0.2 s	OPTROD, Russia, formulation	2
PSPL4 (pyrene)	Conventional	NA	NA	0.172 s	OPTROD, Russia, formulation	2
PSPF2 (pyrene)	Conventional	NA	NA	0.1–2.6 ms	OPTROD, Russia, formulation	2
PF2B [Ru(dpp)]	Conventional	13	5	0.48 s	McDonnell Douglas formulation	9
PF2B [Ru(dpp)]	Conventional	15	5	0.88 s	McDonnell Douglas formulation	9
PF2B [Ru(dpp)]	Conventional	25	5	1.2 s	McDonnell Douglas formulation	9
PF2B [Ru(dpp)]	Conventional	35	5	2.4 s	McDonnell Douglas formulation	9
PtOEP/polymer	Conventional	19	50	0.82 s	Concentrate luminophore near outer surface of the binder	9
PtOEP/GP197	Conventional	22	50	1.4 s		9
PtOEP/GP197	Conventional	26	50	1.6 s		9
PtOEP/GP197	Conventional	32	50	2.4 s		9
Ru(dpp)/RTV	Conventional	6	5	22.4 ms		15
Ru(dpp)/RTV	Conventional	11	5	58.6 ms		15
Ru(dpp)/RTV	Conventional	16	5	148 ms		15
Ru(dpp)/RTV	Conventional	20	5	384 ms		15
Ru(dpp)/PDMS	Conventional	4–5	5	3–6 ms		15
PtOEP/GP197	Conventional	NA	50	2.5 s		5
PtOEP/co-polymer	Conventional	NA	50	0.4 s		5
H_2TFPP/silica	Conventional	NA	NA	1.5–10 ms	Silica with a binder	5
H_2TFPP/TLC	Porous	NA	NA	25 μs		5
Luminophore/AA	Porous	NA	NA	18–90 μs	Depends on luminophore and anodization processes	2
Ru(dpp)/FIB and alumina	Porous	NA	5	Less than 500 μs	Approached apparatus response time	6
PtTFPP/FIB and alumina	Porous	NA	50	Less than 500 μs	Approached apparatus response time	6
PtTFPP/polymer ceramic	Porous	NA	50	60 μs		6
Ru(dpp)/AA	Porous	6.9	5	34.8 μs		17
Ru(dpp)/TLC	Porous	152	5	65.1 μs		17

[a]Luminophore lifetime.

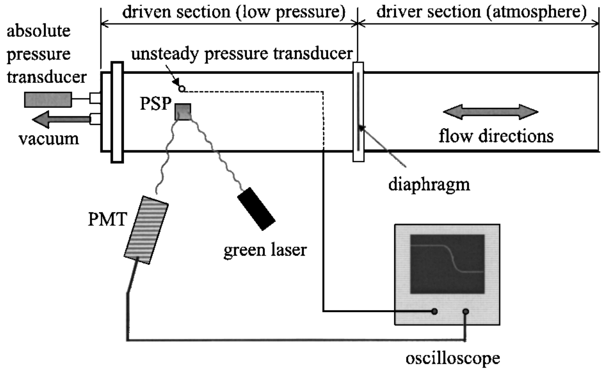

Fig. 2 Schematic of shock tube calibration setup.

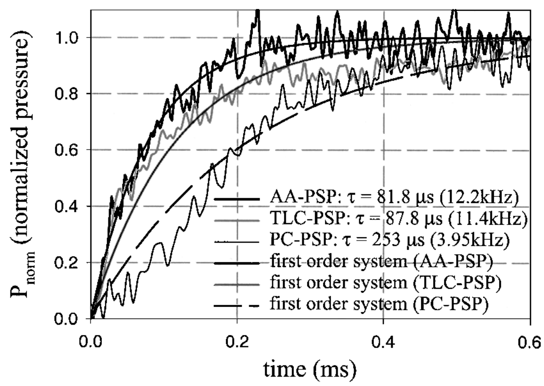

Fig. 3 Response times of porous PSPs measured from shock tube along with curve fits of the first-order system.

the driven section. The PSP is applied to a 25.4-mm-square aluminum block, which is mounted 330 mm from the diaphragm. The aluminum block is a flat surface, mounted flush with the shock tube wall so that pressure variations are not created by intrusion of the sample into the flow. The PSP is excited by a 532-nm laser with a spot diameter of 2–3 mm. The luminescent intensity from the PSP is collected by a photomultiplier tube (PMT) through a 570-nm long-pass filter. The readout voltage from the PMT is collected by a digital oscilloscope. The trigger is set at the first step change of PMT voltage, which corresponds to the first step change of the pressure.

Step Change of Pressure

Figure 3 shows the response of porous PSPs (AA-PSP, TLC-PSP, and PC-PSP) to a theoretical step change in pressure. The luminescent intensity signals are converted to pressures using the unsteady pressure transducer measurements as a reference. A first-order system such as[9]

$$P_{\text{norm}} = 1 - e^{-(t/\tau)} \tag{2}$$

is used to characterize the response time τ, where P_{norm} is normalized pressure and t is time. A detailed procedure and the assumption of a first-order method are described by Sakaue and Sullivan.[17] The measured response times of AA-PSP, TLC-PSP, and PC-PSP are 81.8 ± 1.56, 87.8 ± 2.02, and 253 ± 6.58 μs, respectively, based on the statistical curve fit of Eq. (2) to the shock tube results.

Unsteady Flowfield Measurement of an Oscillating Jet

Fluidic Oscillator

The miniature fluidic oscillator, shown in Fig. 4, is a device that produces an oscillating jet when supplied with a pressurized fluid.[18–21] The oscillating motion of the jet is created by the interaction of two jets inside an internal mixing chamber before the fluid exits the oscillator. The flow pattern of the fluidic oscillator is shown in the schlieren images in Fig. 5. The hot-film probe, as seen in the images, is used for triggering the light source for the camera. R-134a refrigerant gas is used as a supply fluid for these images because it can be easily viewed with schlieren instrumentation. Notice that the jet varies in a sawtooth fashion. The 0-deg phase is defined as the flow position at the point when the hot-film signal triggers the light source. These images serve as a useful reference when compared to the images acquired with PSP.

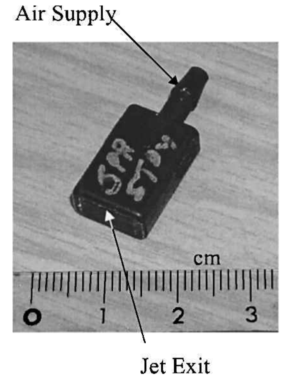

Fig. 4 Photograph of a fluidic oscillator.

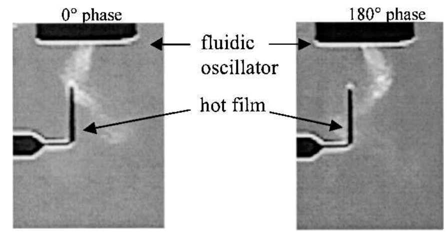

Fig. 5 Schlieren pictures of jet oscillation from a fluidic oscillator.

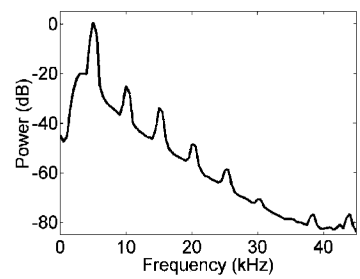

Fig. 6 Normalized power spectrum of the oscillating jet, measured by hot-film probe.

The hot-film probe shown in Fig. 5 is also used to determine the frequency content of the oscillating jet. The signal from the hot-film probe is acquired digitally, and a plot of the power spectrum is generated from the raw signal, as shown in Fig. 6. Note that the hot-film probe used for these measurements has a specified maximum frequency response of 10 kHz. As the oscillator operates at 5 kHz, the flowfield has its primary frequency peak in the power spectrum at 5 kHz. In addition to the primary frequency, there is higher-order frequency content in the flow, ranging up to 30 kHz.

Oscillating Jet Setup

Figures 7a and 7b show photographs and a schematic of the equipment setup for the oscillating jet experiments, respectively. A porous PSP sample is placed under the fluidic oscillator and nitrogen gas from the oscillator is oriented parallel to the PSP sample. An array of blue light-emitting diodes (LEDs) is used as an excitation source and a Photometrics 12-bit charge-coupled device camera with 512 by 752 pixels is used to capture the PSP images through a 580-nm long-pass filter.

In this setup, the camera is exposed for a period of time much longer than the flow oscillation period. The excitation source is pulsed and synchronized with the flow oscillation at a fixed position. The camera exposure time is set so that enough signal level is acquired. Therefore, the camera exposure time varies between porous PSP samples because of variations in luminescent intensity between the samples. The pulse timing is controlled by a miniature electret condenser microphone, which detects the flow oscillation and triggers the blue LEDs through a pulse generator. A short pulse

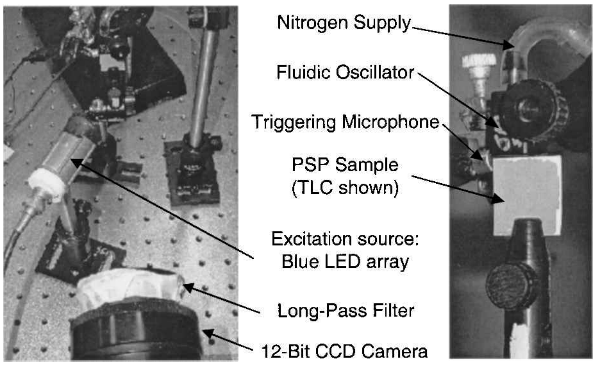

Fig. 7a Photographs of oscillating jet experimental setup.

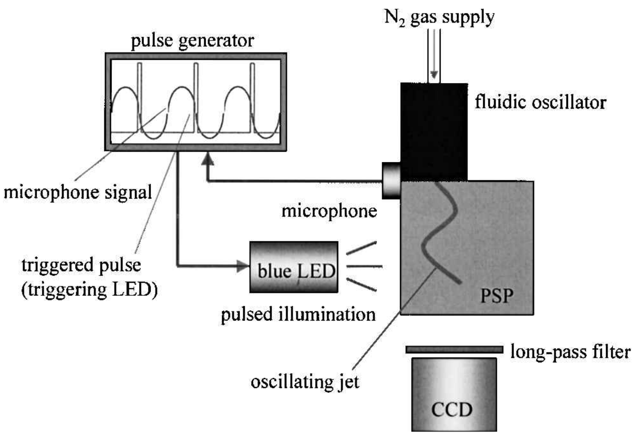

Fig. 7b Schematic of oscillating jet experimental setup.

width is required to obtain images that are not blurred. Therefore, a light pulse of 12 μs is used, which corresponds to 6% of the flow period when the fluidic oscillator operates at 5 kHz. A trigger delay setting on the pulse generator allows the acquisition of flow images at different phase positions.

Fluidic Oscillator Unsteady Flow Images

Figure 8 shows the flow pattern of the fluidic oscillator at various phases, obtained by AA-PSP, TLC-PSP, and PC-PSP. The PSP images are ratioed with a reference image to eliminate the effects of paint and illumination nonuniformities. The images are normalized from air to pure nitrogen so that higher values on the image scale indicate brighter paint luminescence caused by the oscillating nitrogen flow. The presence of nitrogen gas displaces the oxygen molecules from the paint layer so that the luminescent intensity signal of the paint in the flow increases. A distinct sawtooth pattern can be seen in the flow, very similar to the flow shown in the schlieren images of Fig. 5.

The flow images of TLC-PSP are captured with a camera exposure time of 10 s, which corresponds to 50,000 light pulses. As the phase angle is increased, the flow moves to the left, seen by tracing the brighter region of the PSP images. TLC-PSP has a response time of 11.4 kHz so that it is fast enough to capture the oscillating flow. However, the images are not as sharp as the images obtained from AA-PSP and PC-PSP.

The images of AA-PSP are obtained with a camera exposure time of 11 s (55,000 pulses). Although a longer exposure time is required, due to the low luminescent intensity of AA-PSP, these exposures provide the clearest images of the three porous PSPs. The response time of this PSP is 12.2 kHz, which is fast enough to capture the jet oscillation.

The shortest camera exposure time of 0.5 s is used to obtain the PC-PSP images, which corresponds to 500 pulses during the exposure. PC-PSP gives the brightest luminescent signals of the

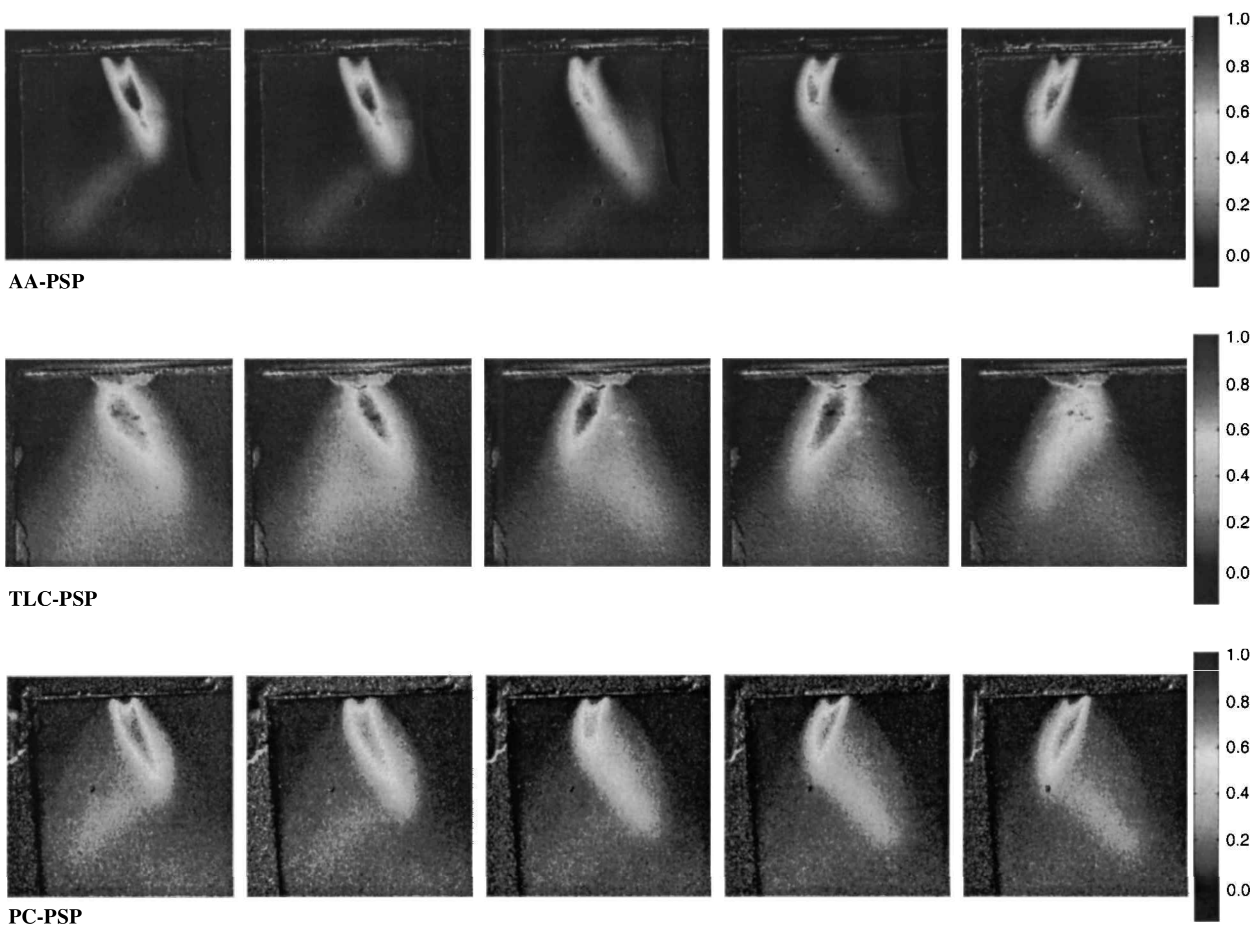

Fig. 8 Jet oscillation from a fluidic oscillator.

three porous PSPs used. However, the response time of this PSP is 3.95 kHz, which is the same order of magnitude as the primary oscillation frequency (5 kHz).

Conclusions

Fast responding porous PSP is used to demonstrate the measurement of unsteady flowfields. Porous PSPs with bathophenruthenium as a luminophore are used with AA, TLC, and PC as the porous supporting matrices. The response times of these PSPs, as characterized by a shock tube, are 81.8, 87.8, and 253 μs for AA-PSP, TLC-PSP, and PC-PSP, which corresponds to 12.2, 11.4, and 3.95 kHz, respectively.

The flow oscillations of a fluidic oscillator are used to demonstrate the capabilities of porous PSP in unsteady flowfields. Flow oscillations of various phases are captured by AA-PSP, TLC-PSP, and PC-PSP for fluidic oscillation tests, with AA-PSP giving the sharpest images.

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