

Depth-Resolved Viscous Entropy Generation in a Semi-Circular Zigzag PCHE Measured by Refractive-Index-Matched PIV

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1. Introduction

In a zigzag PCHE channel the gain in heat transfer comes at the cost of pressure drop, and most of that penalty arises at the bends. In design the bend is represented by a friction factor or a loss coefficient, one number for the whole channel [1,2], and that number has to hold from gas-cooled intermediate heat exchangers in the laminar to transitional regime ($Re \approx 900$ to $4,100$) [2] to supercritical CO_2 regenerators in the fully turbulent regime ($Re \approx 5,000$ to $32,000$) [3]. That number does not indicate where inside the bend the loss is produced.

Separation and recirculation at each bend govern both the heat transfer and the loss, yet the bend itself has rarely been measured directly. Helium testing of a PCHE with zigzag channels reports Fanning friction factor and Nusselt number correlations for the channel as a whole [1], and the loss at the bend is subtracted using a handbook coefficient that the authors themselves describe as uncertain [2]. A numerical study reduces the same geometry to Nusselt-number and friction-factor correlations obtained from simulation alone, without measurement [3]. In both the measured and the computed work the bend is reduced to a coefficient before it is resolved.

That single number is the integral of a field. Entropy is generated as local viscous dissipation, the rate at which velocity gradients dissipate mechanical energy at each point of the flow. The pressure drop of a bend is the volume integral of that field, so a correlation can match the measured drop while placing the source of the loss in the wrong part of the channel. A design intended to suppress the loss, or a model checked only against the drop, therefore needs the field and not just the total. That field cannot be assumed uniform through the channel depth. In a semi-circular zigzag channel, the corner and the cross-section together drive longitudinal vortices over a range of Reynolds numbers that include those measured here [4]. The chord also narrows toward the curved apex, so each depth samples a different section of the same turn. The generation scales with the square of the velocity gradient, so its dependence on the choice of plane cannot be read off the velocity field it is formed from. The generation itself has to be measured plane by plane.

Two optical constraints have limited that measurement. The first is size, since the channels of a working PCHE

have hydraulic diameters of 1 to 2 mm [1,2], too small for velocity gradients to be resolved at the vector density that a dissipation field requires. The second is refraction, since the curved wall of a semi-circular channel bends the line of sight and the interior remains inaccessible unless the refractive index of the working fluid is matched to that of the test section. PIV in a semi-circular zigzag channel has been performed without index matching, imaging a water flow through the flat face of an acrylic module [5]. That work stayed in the laminar to transitional regime and reported the vortex length downstream of the bend, one number for each Reynolds number. It gives the extent of the recirculation but not the location of the loss.

This study measures the velocity field and the viscous entropy generation field inside a semi-circular zigzag PCHE bend, rather than a single integrated loss coefficient. The measurement is made on three depth planes at three turbulent Reynolds numbers. On each plane the site of the generation is located relative to the reversed region recorded on that same plane, and the three planes then show whether that relation holds as the depth changes. Simulations of this geometry have not been validated against measurements of this kind.

2. Experimental Method

2.1. Test loop and refractive-index-matched fluid

A single channel of a diffusion-bonded zigzag PCHE was reproduced at an enlarged scale as a transparent test section, printed by stereolithography in Clear V5 resin (Formlabs). Its cross-section is a semicircle of radius $R = 15$ mm, so the hydraulic diameter is $D_h = 18.33$ mm. The path has a pitch of 120 mm and a bending angle of 20° , each straight segment being inclined 20° to the mean flow direction so that the flow turns through 40° at every corner. Straight sections of 300 mm and 240 mm precede and follow the zigzag path. The test section is mounted in a closed flow loop driven by an inverter-controlled pump as in Fig. 1, with the loop temperature held to within $0.2^\circ C$ during each run by an in-line heat exchanger and measured by a K-type thermocouple on the pipe centerline. The volumetric flow rate was measured with a clamp-on flowmeter (KEYENCE FD-H32).

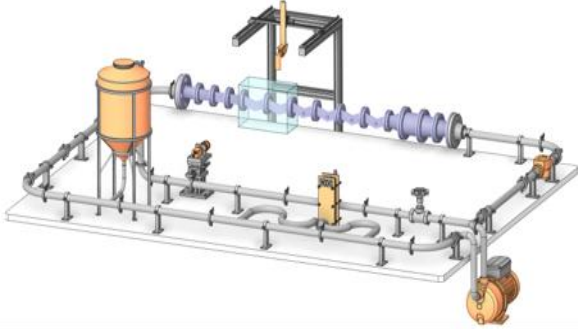


Fig. 1. Closed flow loop with the transparent test section at the center.

The curved channel walls act as lenses, so particle images near them are refracted and displaced unless the refractive index of the fluid matches that of the resin. The working fluid is a binary mixture of benzyl benzoate and isopropyl myristate at a volume ratio of 84:16, which matches Clear V5 at $n = 1.546$ for a printing layer thickness of 0.025 mm. Density and viscosity vary with temperature but enter only through the Reynolds number, and both are evaluated at the temperature of each run. The density is taken from the volume-weighted mixture value at 20 °C and corrected with $dp/dT = -0.462 \text{ kg m}^{-3} \text{ }^{\circ}\text{C}^{-1}$. A drift in refractive index is different, because it distorts the images as they are formed, and that distortion cannot be undone afterward. The equilibrium temperature of the loop is set by the pump work and rises with flow rate, so the three Reynolds numbers settle at different temperatures. Within a run, the in-line heat exchanger held the temperature to within 0.2 °C, and across the three planes of a given Reynolds number it varied by at most 0.8 °C, which at $dn/dT \approx -3.9 \times 10^{-4} \text{ }^{\circ}\text{C}^{-1}$ limits the index drift to 3×10^{-4} for the depth comparison. The match was verified with a refractometer before each run, and Table I lists the temperature range of each Reynolds number group [6].

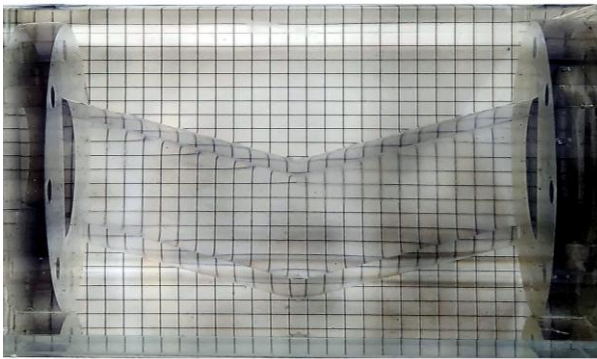


Fig. 2. 3D-printed semi-circular zigzag PCHE test section in the refractive-index-matching solution.

2.2. PIV system and image processing

Two-component velocity fields in the plane of the light sheet were recorded with a MicroVec 2D PIV

system. Fluorescent Rhodamine B tracers of 15 μm mean diameter and 1.1 g/cm^3 density, within 3 % of the density of the working fluid, were used as seeding. Their 580 nm emission is separated from the 532 nm laser reflections at the resin walls, where the velocity gradients are steepest. A pulsed Nd:YAG laser (MicroVec PIVotal-200, 532 nm, 200 mJ per pulse) formed the light sheet, and 2756×2208 pixel image pairs were recorded by a 6-megapixel CCD camera (Imperx Bobcat B2750M, 4.54 μm pitch, 12-bit) through a 100 mm lens, synchronized by a MicroVec MicroPulse 825 timing unit.

The image scale was set with a rectangular target of $22 \times 70 \text{ mm}$ placed in the measurement plane. Its 73.376 mm diagonal spans 1,442 pixels, giving $S = 0.0509 \text{ mm}$ per pixel over a $140.2 \times 112.4 \text{ mm}$ field of view. The inter-frame time was then set for each Reynolds number so that the bulk displacement is 2.64 pixels in all nine cases (Table I), which makes the error terms that scale with the displacement the same throughout. Vector fields were computed by cross-correlation on a 32×32 pixel interrogation window at 50 % overlap, giving a vector pitch of 0.81 mm. A mask was drawn separately for each of the nine cases to exclude the walls and the optically invalid regions, and one mask and one set of correlation parameters were used for every image pair of a case. The mask removes about one vector pitch at each wall, so 31 to 34 vectors span the channel.

PIV records the motion of the tracer, so how faithfully the tracer follows the fluid was checked with the Stokes number. Its relaxation time $\tau_p = \rho_p d_p^2 / 18\mu$ is 2.1 to 2.3 μs , against a bulk flow timescale $\tau_f = D_h / U_b$ of 4.5 to 7.7 ms and a Kolmogorov timescale $\tau_\eta = \sqrt{(\nu / \epsilon)}$ of 0.04 to 0.09 ms, estimated with $\epsilon \approx U_b^3 / D_h$. The Stokes numbers are therefore 3 to 5×10^{-4} on the bulk scale and 0.02 to 0.06 on the Kolmogorov scale, both below the $St < 0.1$ criterion, so the fluctuations are followed as faithfully as the mean motion. The gravitational settling velocity is below 0.7 $\mu\text{m/s}$ and is negligible at these bulk velocities.

2.3. Measurement conditions

Measurements were taken on three depth planes of the same bend, P1 to P3 at $z = 12, 10$ and 8 mm from the bottom of the semi-circular cross-section ($z/D_h = 0.655, 0.546$ and 0.436), and at three bulk Reynolds numbers, giving nine cases. The positions of the planes within the cross-section are shown in Fig. 3. The conditions are given in Table I. The flow rate and temperature are the ranges indicated during each run. The derived rows use the run midpoints, and each column spans the three runs of its group.

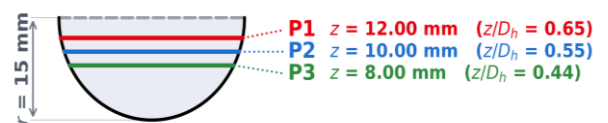


Fig. 3. Positions of three planes (P1, P2, P3) within the flow channel cross-section.

Table I. Measurement conditions.

	Re 7,000	Re 10,000	Re 13,000
Re (actual)	7,030~7,055	10,039~10,176	13,302~13,393
Q (L/min)	50.2~50.7	69.7~70.4	86.2~86.8
U _b (m/s)	2.377~2.379	3.301~3.306	4.077~4.079
T (°C)	28.5~28.8	30.1~30.9	34.2~34.7

2.4. Entropy generation field and reference structures

Entropy generation in a convective flow arises from two sources of irreversibility, heat conduction down a finite temperature gradient and viscous friction. The local volumetric entropy generation rate is the sum of the two [7],

$$\dot{S}'''_{\text{gen}} = \frac{k(\nabla T)^2}{T^2} + \frac{\mu\Phi}{T} \quad (1)$$

Only the viscous term of Eq. (1) is used here. A two-component velocity field determines that term but not the conduction term, which needs a temperature field that the present measurement does not provide. The flow is also close to isothermal, and the heat added by the pump is removed by an in-line plate heat exchanger that holds the loop to within 0.2 °C through each run.

That term is set by the in-plane viscous dissipation function, which for a two-dimensional incompressible flow is formed from the four in-plane gradients of the time-averaged velocity field [7],

$$\mu\Phi = 2\mu\left(\left(\frac{d\bar{u}}{dx}\right)^2 + \left(\frac{d\bar{v}}{dy}\right)^2\right) + \mu\left(\frac{d\bar{u}}{dy} + \frac{d\bar{v}}{dx}\right)^2 \quad (2)$$

The gradients normal to the light sheet are not accessible to a two-component measurement, and every term they would add to Eq. (2) is a square, so the quantity mapped here is a lower bound on the full three-dimensional dissipation.

Differentiating a PIV field amplifies its noise, so the mean velocity is first smoothed with a Gaussian of half a vector pitch, extended across the mask boundary by normalized convolution. It is then differentiated by second-order central differences on the vector grid and masked back to the measured region [7]. Extending across the boundary rather than masking the stencil there keeps a complete stencil on the row of vectors nearest the wall, which is where the generation is largest. At the two ends of the imaged channel the section is cut across the flow with nothing to extend into, so five vectors are discarded at each end.

Two requirements set the filter width. The filter must extend the field past the mask, and its full width at half maximum of 0.96 mm must stay inside the 1.63 mm interrogation window so that the correlation and not the filter sets the resolution [8]. Smoothing does lower a quantity built from the square of a gradient. However, at this width, the ninety-ninth percentile of the field away

μ (cP)	6.62~6.64	6.37~6.45	5.97~6.01
ρ (kg/m ³)	1071.08~ 1071.17	1070.11~ 1070.43	1068.35~ 1068.54
Δt (μs)	56.6	40.7	33.0
N pairs	312	312	312

from the mask edge falls only to 87 % of its unsmoothed value while the median falls by three percent. Every statement below also held unchanged when the width was varied from a quarter to two vector pitches.

The generation is normalized by the mechanical energy flux of the bulk flow as $\dot{S}^* = \mu_i\Phi D_h/(\rho_i U_{b,i}^3)$, with ρ_i , μ_i and $U_{b,i}$ taken from Table I, so that the nine cases share one scale. The temperature is uniform over a plane during its run, so the local viscous entropy generation rate $\mu\Phi/T$ differs from $\mu\Phi$ by a constant and $\dot{S}^*$ is a property of the measured velocity gradients alone. Only the location of the generation is used in what follows. The vector pitch is 0.81 mm. The interrogation window of 1.63 mm and the filter width of 0.96 mm combine in quadrature to an effective resolution of 1.9 mm. That is 80 to 130 Kolmogorov lengths at these Reynolds numbers, the Kolmogorov length being estimated from a bulk dissipation rate of the cube of the bulk velocity divided by the hydraulic diameter. The magnitude of the generation is therefore not resolved, and the mapped values are not a measurement of how much entropy is generated. The measurement locates the generation relative to the reversed region and shows how that location changes with depth.

3. Results and Discussion

3.1. Flow structure and viscous entropy generation

The overall flow structure is examined first from the velocity fields. Fig. 4 shows the mean velocity magnitude of the nine cases, each normalized by its own bulk velocity. The depth planes are in rows and the Reynolds numbers in columns, and streamlines of the in-plane mean flow are overlaid. Coordinates are scaled by the hydraulic diameter from the lower corner of each measured field at its upstream end. The streamwise coordinate x increases along the flow and the bend corner falls near $x/D_h = 2$. The wall-normal coordinate y is measured from the lower wall at that station and becomes negative over the floor of the bend. The flow runs from right to left. A low-velocity region forms on the wall downstream of the corner, and within it the streamlines close into a loop. That loop is the recirculation, and the reversed region it encloses is where the streamwise mean velocity changes sign. The loop is widest on the shallowest plane at the lowest Reynolds number, and it contracts as the Reynolds number rises and again as the plane moves deeper into the channel. The reversed region is therefore smallest where both trends act together, and at Re 13,000 the contraction is complete, so that on the deepest plane the streamlines sweep past the corner

without closing. A recirculation is therefore present in eight of the nine cases.

The near-wall generation does not follow the recirculation. Fig. 5 gives $\dot{S}^*$ for the same nine cases on one common logarithmic scale. The generation is confined to thin layers along both walls, and more than two orders of magnitude separate the near-wall maximum from the core. The layer stands out along the wall downstream of the inner corner, the same wall where the recirculation sits. A comparison with Fig. 4 shows that the maximum lies outside the reversed region in every case that has one, and inside that region $\dot{S}^*$ stays far below the near-wall band because the velocity gradients there are small. The band follows instead the shear layer that separates the reversed flow from the accelerated stream beneath it, continuing along the wall past the point where that layer reattaches. Since $\dot{S}^*$ is normalized by the cube of each case's own bulk velocity, a comparison across Reynolds numbers would reflect that normalization as much as the flow, so the planes are compared at fixed Reynolds number. The deepest plane at Re 13,000 is then the decisive case, because no reversed region remains there while the near-wall band persists along the same wall, so the wall concentration does not depend on the recirculation being closed. The loss is produced in the shear layer, not in the recirculation.

The reason lies in the definition of the generation. It grows with the square of the velocity gradient, so the reversed region contributes little even though it covers a large part of the section, while the thin layer that separates the reversed flow from the accelerated stream contains the largest gradients in the field. A measurement that reports only the length of the vortex, as the earlier PIV of this geometry does [5], therefore determines the

extent of the recirculation but not where the loss is produced.

The separated structure changes with depth while the wall generation does not, so no single plane can represent the bend. A model that reproduces the extent of the reversed region without resolving the layer that bounds it will put the loss in the wrong place.

The values reported here are a lower bound in two ways. The gradients normal to the light sheet would add positive terms to Eq. (2), and the near-wall layer is thinner than the interrogation window, so its peak is smoothed. Neither limit moves the band relative to the reversed region, which is what the comparison rests on.

3.2. Uncertainty of the velocity and of the derived generation field

The budget in Table II follows the framework of Sciacchitano for planar PIV [9] and the definitions of the ISO-GUM. Sources that keep their sign from one recording to the next are distinguished from those that scatter about zero since averaging suppresses the second and leaves the first. Each enters through a measured quantity, the image scale or the displacement itself, and the pulse interval contributes only a negligible timing jitter. Each is converted to a velocity through its own sensitivity coefficient before they are combined. They are then summed in quadrature, $u_c^2 = u_{sys}^2 + u_{ran}^2$, and the root of that sum is the combined standard uncertainty. A coverage factor $k = 1.96$ expands it to $u_c = k u_c$, the 95 % confidence interval of a normal distribution. Averaging the $N = 312$ fields of a plane reduces the random sources by $\sqrt{N}$ and leaves the systematic ones unchanged.

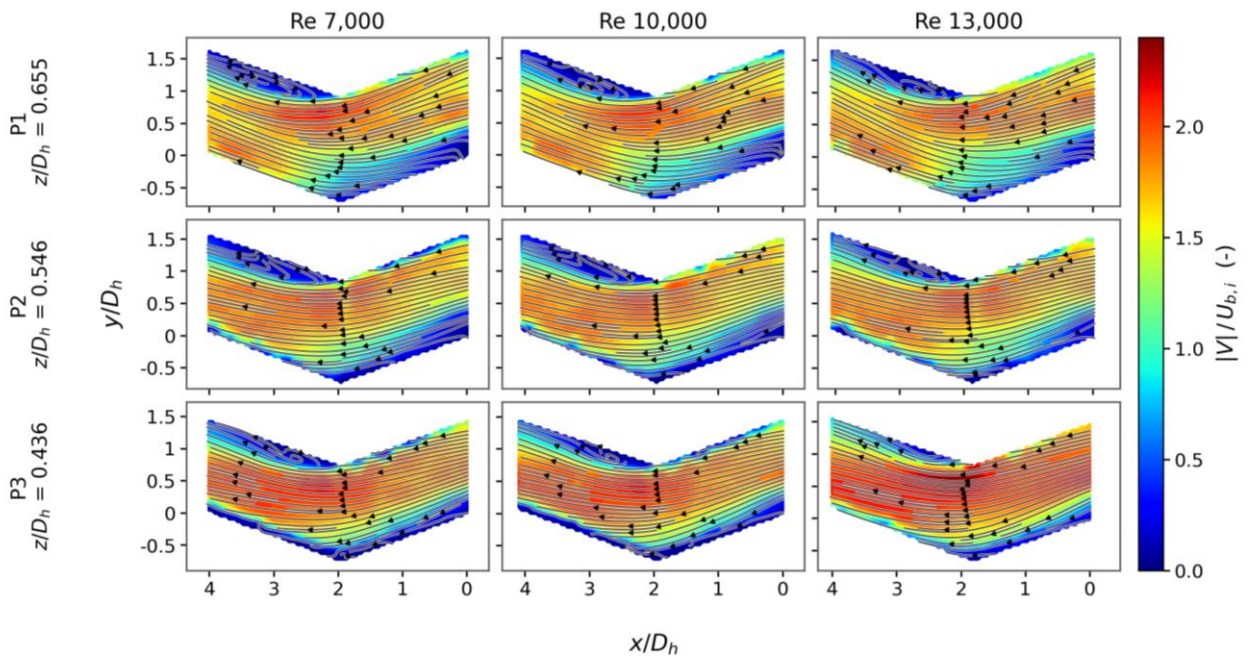


Fig. 4. Mean velocity magnitude $|V|/U_{b,i}$ on three depth planes (rows) at three Reynolds numbers (columns), on a common scale. Coordinates are scaled by the hydraulic diameter, with y negative over the floor of the bend. Lines are streamlines of the in-plane mean flow. Flow is from right to left.

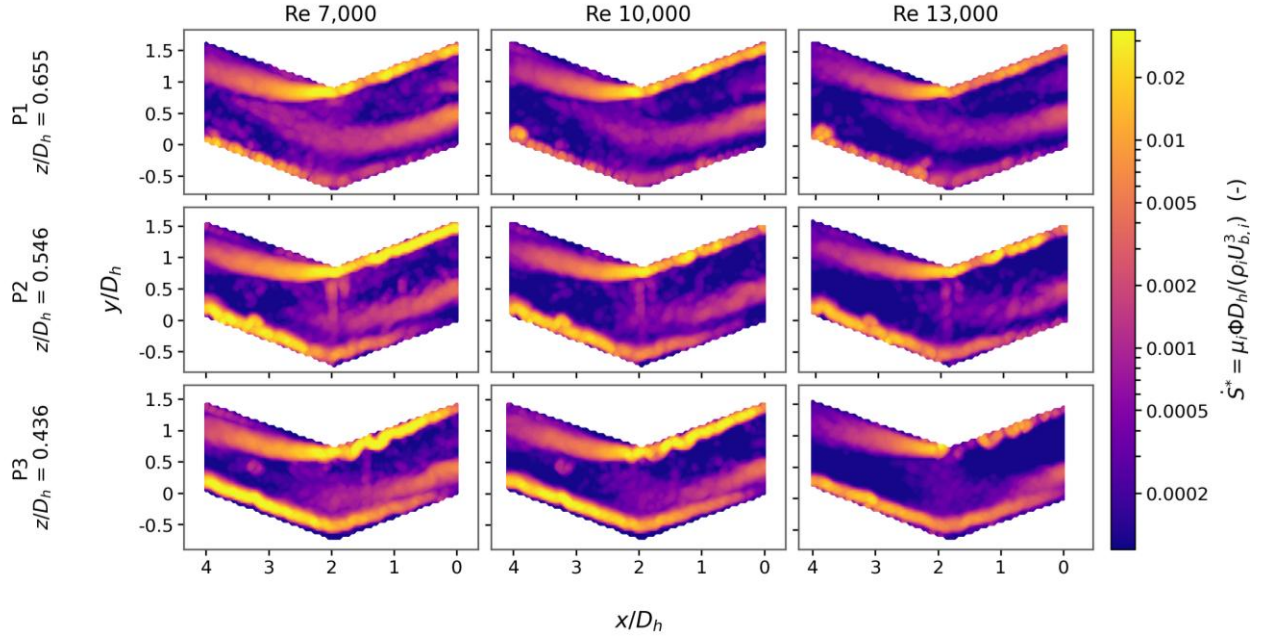


Fig. 5. Normalized viscous entropy generation $\dot{S}^*$ on one common logarithmic scale. Cases and axes as in Fig. 4. Flow is from right to left.

Table II. Velocity uncertainty budget as a percentage of the bulk velocity of each case. Values separated by a slash are the median and the highest one percent of a plane, and a range spans the nine cases.

Source	Enters through	Systematic or Random	Value
Statistical convergence of the time mean, streamwise $\sigma/\sqrt{N}$	ΔX	Random	2.4 / 4.5
Sub-pixel correlation, 0.1 px per vector	ΔX	Random	0.2
Peak locking, $C/\sqrt{2}$ with $C = 0.092$ to 0.146 px measured on the validated vectors of the instantaneous fields	ΔX	Systematic	2.5~3.9
Image scale, 0.1 mm in 73.376 mm	M	Systematic	0.14
Combined standard uncertainty			3.5~4.6 / 5.1~5.9
Expanded uncertainty, $k = 1.96$			6.8~9.0 / 10.0~11.6

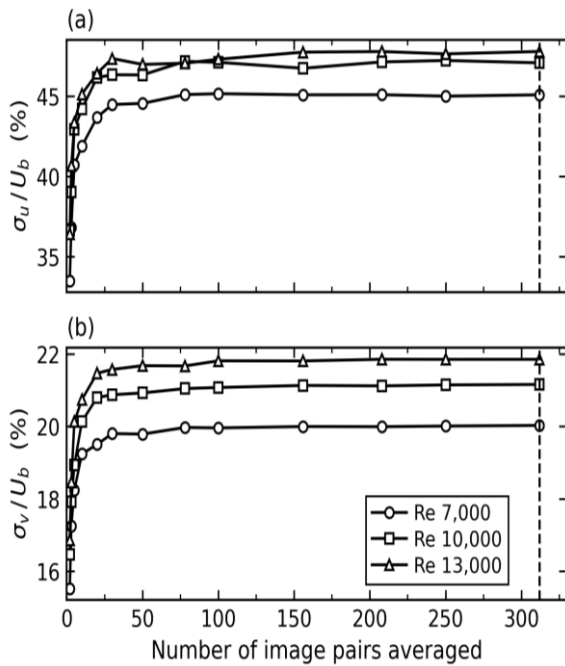


Fig. 6. Convergence of the temporal standard deviation on plane P2 for (a) U and (b) V. The dashed line marks $N = 312$.

Table I reports each condition as a range because the loop settles at its own temperature rather than holding a set point. Within a group the three planes differ by at most 1.4 % in Reynolds number, and the sign of that drift is not the same in the three groups, so this difference cannot be the cause of a trend with depth that all three groups share. That range is the difference between the three runs of one group and not an error in any single run. It is also separate from the 3.5 % accuracy of the Reynolds number itself, which is dominated by the ± 3.0 % flowmeter. The temporal standard deviation that enters the statistical term of Table II has converged well before $N = 312$ (Fig. 6). Splitting the 312 fields of a plane into two independent halves reproduces the same value, 2.4 % of the bulk velocity, without assuming the form of the statistical term. In every case with a reversed region, both halves place the highest one percent of the near-wall generation outside the reversed region, the ordering on which the comparison above rests. Vectors that failed validation against their eight neighbors were replaced by the local median, and because such interpolated vectors dilute the locking signature, the peak locking amplitude in Table II is measured on the validated vectors alone. The masks place the planes within 0.2 mm of their nominal depths.

4. Conclusions

Refractive-index-matched PIV mapped the viscous entropy generation of the in-plane mean flow of a semi-circular zigzag PCHE bend on three depth planes at three turbulent Reynolds numbers. The generation is confined to thin near-wall layers more than two orders of magnitude above the core, and its maximum lies in the near-wall shear layer downstream of the corner rather than inside the recirculation. The recirculation is present in eight of the nine cases, and at Re 13,000 it is absent from the mean field on the deepest plane. A single plane therefore cannot represent the bend. These depth-resolved fields place the loss inside the bend rather than lumping it into a pressure drop, and so give a channel model the location of the loss to be tested against.

Acknowledgments

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