

Experimental quantification of heat haze errors in stereo-DIC displacements: Application to thermoplastics thermoforming temperature range

Aniket Ghosh Dastidar, Abderrahmane Ayadi^{*} , and Marie-France Lacrampe

IMT Nord Europe, Institut Mines-Télécom, Univ. Lille, Centre for Materials and Processes, 59000 Lille, France

Received: 23 December 2022 / Accepted: 5 September 2023

Abstract. Stereo digital image correlation (Stereo-DIC) is recurrent in photo-mechanics to measure kinematic fields which can be of high interest for instrumenting open-mould forming processes. Nevertheless, in the presence of pre-heating operations, as observed in the context of thermoforming processes, natural convective heat flows risk emerging and causing optical distortions in the recorded images. Consequently, this alters the precision of the measured full-fields of displacements. To address these challenges, this study proposes an experimental approach with two distinctive features. Firstly, it focuses on regenerating the heat haze effect at a laboratory scale within a partially opened vertical enclosure and without utilizing any filtering air flows. Secondly, the study quantifies the spatial and temporal variations of errors through statistical analyses of the differences between measurements obtained from quasi-static speckle translations and known imposed displacements. Experimental results indicate that the main cause of displacement errors is related to the 3D nature of the hot air turbulence caused by the natural convection phenomenon. This observation is supported by the detection of feather-shaped heat flows causing optical out-of-plane surface deviations. Furthermore, the study validates the possibility of obtaining time-dependent corrective functions for bias errors, which characterize the performance of the calibrated Stereo-DIC system in the presence of heat haze. Despite the limitation of extensive measurements required by the proposed approach, this study contributes to addressing the heat haze effect and constitutes a step towards extending the use of stereo-DIC for in-situ instrumentation of short-duration thermomechanical tests in the presence of heat haze.

Keywords: Stereo-DIC / systematic errors / random errors / heat haze / thermoforming

1 Introduction

Stereo-digital image correlation (stereo-DIC) is a metrological technique with the potential to provide three-dimensional kinematic fields through the use of stereo-vision and digital image correlation algorithms [1,2]. Its application in instrumenting open-mould forming processes constitutes one potential case of application of stereo-DIC, enabling the tracking of mechanical deformations a material undergoes under realistic forming conditions. Within the specific range of thermoforming temperatures for thin thermoplastic sheets (at relatively high temperatures below 300°C), stereo-DIC has effectively demonstrated its ability to achieve the following: characterizing out-of-plane instabilities during pre-stretching operations [3–5], measuring polar deflections during bulge operations [6], mapping full

fields of thicknesses during plug-assisted forming [3,7,8], and controlling forming aspect ratios during the hot-bending of thin thermoplastic sheets [9]. Despite the existence of a broad consensus within the material forming community to adhere to general guidelines such as those provided by the International Digital Image Society for using stereo-DIC measurements [10], the lack of standards for conducting measurements in industrial environments still require more efforts to acquire reliable metrological data for control or certification tests [11–13]. Indeed, potential extrinsic sources of errors (such as changes in luminosity, vibrations, and the presence of heat sources) have been reported to cause optical flaws in images used as input for correlation algorithms, ultimately leading to inaccurate kinematic fields [14–17]. To address these sources of errors, studies in uncertainty-quantification are conducted to either (i) quantify errors and uncertainties and/or (ii) correct these errors to provide reliable metrological data [18–20].

^{*} e-mail: abderrahmane.ayadi@imt-nord-europe.fr

The utilization of industrial thermoforming equipment often involves the presence of thermal gradients at relatively high temperatures. These gradients act as precursors to both thermal phenomena (such as natural convective heat fluxes, including buoyancy effect) and optical phenomena (such as the heat haze effect). The heat haze effect in particular refers to an optical distortion observed in the air near hot surfaces due to local temperature variations. It occurs in an optical field when light rays pass through the hot air near the hot material towards the cold camera lenses, resulting in deviations caused by local fluctuations in the air's refractive index [20,21]. In the realm of experimental mechanics, researchers have long been exploring DIC measurements in the presence of heat haze sources. A non-extensive literature review indicates that the heat haze effect has primarily been observed in studies involving optical measurements at high temperatures (higher than 300 °C). For instance, the pioneering work by Lyons et al. investigated the accuracy of two-dimensional DIC in measuring displacements and strains at temperatures up to 650 °C, considering different tests involving free thermal expansion, rigid body motion, and uniform tensile loads [22]. Their work confirmed that two-dimensional DIC could effectively assess strains with a level of accuracy comparable to ambient conditions, provided that precautions were taken to: (i) mitigate image distortions due to the optical path's glass quality, and (ii) maintain a constant refractive index of the heated air near the furnace (i.e., filtering heat haze effect by applying forced air flows). In more recent comprehensive studies, other authors such as Berny et al. introduced a spacetime implementation to extend DIC measurements to temperatures exceeding 1200 °C, suitable for applications involving ceramic matrix composites [21]. For temperatures exceeding 600 °C, the same study provided an in-depth review of the literature, providing insights into: (i) the utility of two-dimensional DIC in characterizing creep crack growth, evaluating coefficients of thermal expansion, and more, and (ii) the applicability of stereo-DIC in assessing thermal expansion coefficients of stainless steels. On the other hand, Berny et al. outlined three challenges when conducting DIC measurements at temperatures surpassing 600 °C. These challenges relate to: (i) black body radiations (where image brightness is not conserved), (ii) the lack of image contrast conservation, leading to degradation of white and black speckles at temperatures beyond 300 °C, and (iii) thermal gradients causing fluctuations in the refractive index of the air. In another comprehensive overview paper, Yu et al. similarly reported three challenges that impact the quality of imaged speckles [23]. These challenges include: (i) image intensity saturation due to radiative heat transfer, (ii) deterioration of image contrast caused by speckle degradation, and (iii) image distortion due to heat haze. Heat haze, in this context, refers to the presence of a natural convective heat flux between hot and cold domains within the optical field. When air is heated, local changes in its density and refractive index of light can lead to visually imperceptible distortions of light beams captured by optical cameras [20]. For relatively high temperatures (i.e., up to 300 °C, such as in the thermoforming temperature range of

thermoplastics), Yuile et al. employed CFD simulations to model the thermal field of a regulated thermal chamber to analyze optical distortions during two-dimensional DIC measurements [24]. Their results demonstrated that without forced convective flows for air mixing and cooling, the measured deformation errors induced by heat haze could not be neglected when air temperatures exceeded 60 °C. To quantify and subsequently rectify distortions in recorded optical images at relatively high temperatures, Ma et al. proposed the use of the background-oriented Schlieren (BOS) technique. They further applied temporal averaging to the corrected images before subjecting them to digital image correlation algorithms [25]. Jones et al., on the other hand, assessed the mitigation of image distortions by imposing forced convective air flow cooling within the optical camera's field of view during image acquisition. Additionally, they applied a temporal filter to the images prior to calculating the displacements [6]. Results from both previous studies demonstrated that employing temporal filters was the more effective approach in reducing distortions induced by heat haze, compared to solely relying on forced convective air flow during image acquisition. Despite the considerable efforts mentioned earlier, the complex nature of thermal challenges in industrial-scale thermoforming processes involving thin thermoplastic sheets requires additional work to quantify stereo-DIC errors. This becomes particularly pertinent when heat haze manifests in close proximity to the speckled surface of the heated material rather than directly near the camera. As a result, conventional solutions involving filtering the heat haze effect through forced air flows during image capture can potentially introduce conflicting influences on the thermomechanical behavior of softened thermoplastic sheets during stretching [6] or open-mould forming operations [26,27]. These solutions may inadvertently interfere with in-situ measurements. Although this study does not directly delve into thermoforming or stretching of thermoplastics at high temperatures, the defined experimental work is tightly inspired from previous work by the authors [28].

Compared to the existing studies in the context of thermoplastics thermoforming processes, the current study claims originality by addressing the lack of explicit research regarding the quantification of displacement errors. It contributes, alongside other existing studies in the field of experimental mechanics, to quantifying both systematic and random errors induced by heat haze in stereo-DIC displacement measurements. These claims primarily relate to scenarios where conventional practices, such as turbulent air flow through ventilation, are inapplicable to mitigate heat haze distortions. The laboratory-scale procedure proposed herein and the expected output of the manuscript should be considered in light of the following points in mind: First, the study focuses on regenerating natural convection air flows within a "partially open enclosure" and within the temperature range commonly used for thermoforming High Impact Polystyrene sheets. Second, unlike studies conducted at relatively high temperatures (i.e., below 300 °C), the current research examines the influence of quasi-static speckle translations on measured displacement errors in the presence of heat haze. Third, it evaluates the

performance of a laboratory-scale stereo-DIC system after calibration, which is essential for instrumenting thermoforming rigs, building on the authors' previous work [29]. Lastly, the study hones in on scenarios where heat haze-induced errors cannot be mitigated by forced convective air flows, particularly in the context of in-situ measurements during thermoforming processes. In such cases, introduced air-flows can interfere with the applied thermomechanical loads. As will be later justified in Section 2.2, the study deliberately excludes errors stemming from black body radiations and thermal speckle degradation from its scope.

Consequently, the proposed laboratory-scale procedure relies on unidirectional rigid body translation tests conducted on a tensile machine equipped with an auto-regulated heating chamber. The thermal configuration corresponds to the thermal case of a partially open vertical enclosure [30]. The article's structure unfolds as follows: the experimental part is devoted to the requisite experimental precautions in order to: (i) regenerate heat haze within the thermoforming temperature range of commonly used thermoformable material, high-impact polystyrene (HIPS), and (ii) ensure temporal synchronization between the imposed and measured displacements during mechanical tests. The subsequent sections, encompassing results and discussions, will focus on the macroscale temporal and spatial fluctuations of displacement errors influenced by heat haze. Particular attention will be given to two pivotal parameters: the regulation temperature (T_R) and the displacement speed. The garnered outcomes will then guide the proposition of a time filtering approach for the measured displacements.

2 Material and methods

2.1 Equipment

Unidirectional rigid body motion tests were carried out along the $\vec{Y}$ direction (see Fig. 1a) using the same speckled target plate (i.e., the same specimen) measuring $120 \times 40 \times 3 \text{ mm}^3$. The plate was manufactured through injection moulding of a temperature-resistant grade of short glass fiber-reinforced polyamide 66 commercialized under the name Zytel[®] 70G35HSL by DuPont[®] and having a melting temperature of 263°C and a coefficient of linear thermal expansion of $17 \times 10^{-6} \text{ (K}^{-1}\text{)}$ [31]. Mechanical boundary conditions involved pneumatic clamping of the target plate from its upper side within a tensile machine (Roell-Z010, Zwick[®]) equipped with a temperature chamber (AllroundLine-Z010, Zwick[®]) having inner dimensions of $260 \times 445 \times 700 \text{ mm}^3$ (Fig. 1a). During thermal regulation, the temperature chamber was sealed and uniformly heated using forced convection from an integrated mixing fan that circulated hot air, until it stabilized at the desired regulated temperature, T_R (Fig. 1b). An additional delay of 180s was imposed to stop the mixing fan and allow the target plate's temperature to stabilize. For conducting thermal and optical measurements, an observation window sized $120 \times 140 \text{ mm}^2$ (i.e., covering 9.2% of the surface) was fully opened in the front wall of the temperature chamber (Fig. 1c) to

mimic hot-forming operations. An infrared camera (PI-640i, Optris[®]) captured average temperatures (T_S) from the speckled region of interest, while two CCD cameras (Imager MX-4M, LaVision[®]) recorded stereoscopic images at a fixed frequency of five Hz. These measurements were initiated a few seconds before opening the observation window to allow posteriori synchronization between displacements measured by the stereo-DIC system (denoted by V_i) and those imposed by the tensile machine (denoted by V_t^*). The experimental plan included four temperatures $\{25; 105; 115; 120\}^\circ\text{C}$ and three displacement speeds $\{10; 50; 100\} \text{ mm/min}$. Since the region of interest (ROI) covered $35 \times 30 \text{ mm}^2$, a single test case was considered to provide full fields of displacements from each temperature/speed combination of parameters.

2.2 Speckle characterization

Random speckle patterns were applied to the specimen's surface using paint sprays for experimental characterization. Initially, a layer of mat white paint (Sinto[®], reference 925020) was applied, followed by the application of heat-resistant black paint (ColorWorks[®], reference 918550), capable of withstanding temperatures up to 800°C , to create the black speckle patterns. During conducted "moving specimen" tests the stereovision system captured images of the same speckled specimen under various temperature/speed conditions.

2.2.1 Morphological descriptor of the speckle

Feret's diameter as a morphological descriptor of the black spots within the speckle patterns was analyzed based on the open-source software ImageJ. First, images recorded by the left camera of the stereovision system at time t_0 were selected, then were encoded into 8-bit. Second, automatic Otsu threshold-based binarization was applied, followed by an automatic watershed filter to separate adjacent black spots. Figure 2a illustrates histogram distributions of Feret's diameter. At 25°C (i.e., the reference condition representing the absence of heat haze effects) the average Feret's diameter measured approximately $735 \mu\text{m}$ with a standard deviation of $570 \mu\text{m}$. These speckle patterns closely resembled those employed for instrumentation on an industrial-scale thermoforming rig [3].

2.2.2 Verification of potential effect of blackbody radiation

For qualitative and quantitative verifications, representative images of the speckle corresponding the following time stamps $\{t_0; t_0 + 5s; t_0 + 10s \text{ and } t_0 + 15s\}$ were extracted and were encoded into 8-bit. Then histograms of greylevels were generated and provided in Figure 2b. At 25°C and a speed of 10 mm/min , discernible disparities were observed in the areas under the curves between the test's start at t_0 and at $t_0 + 15 \text{ s}$. Upon escalation to speeds of 50 and 100 mm/min , corresponding to total displacements of 12.5 mm and 25 mm , the histograms exhibited a gradual shift towards brighter greylevels. This shift implied an illumination gradient along the $\vec{Y}$ direction. Quantitative

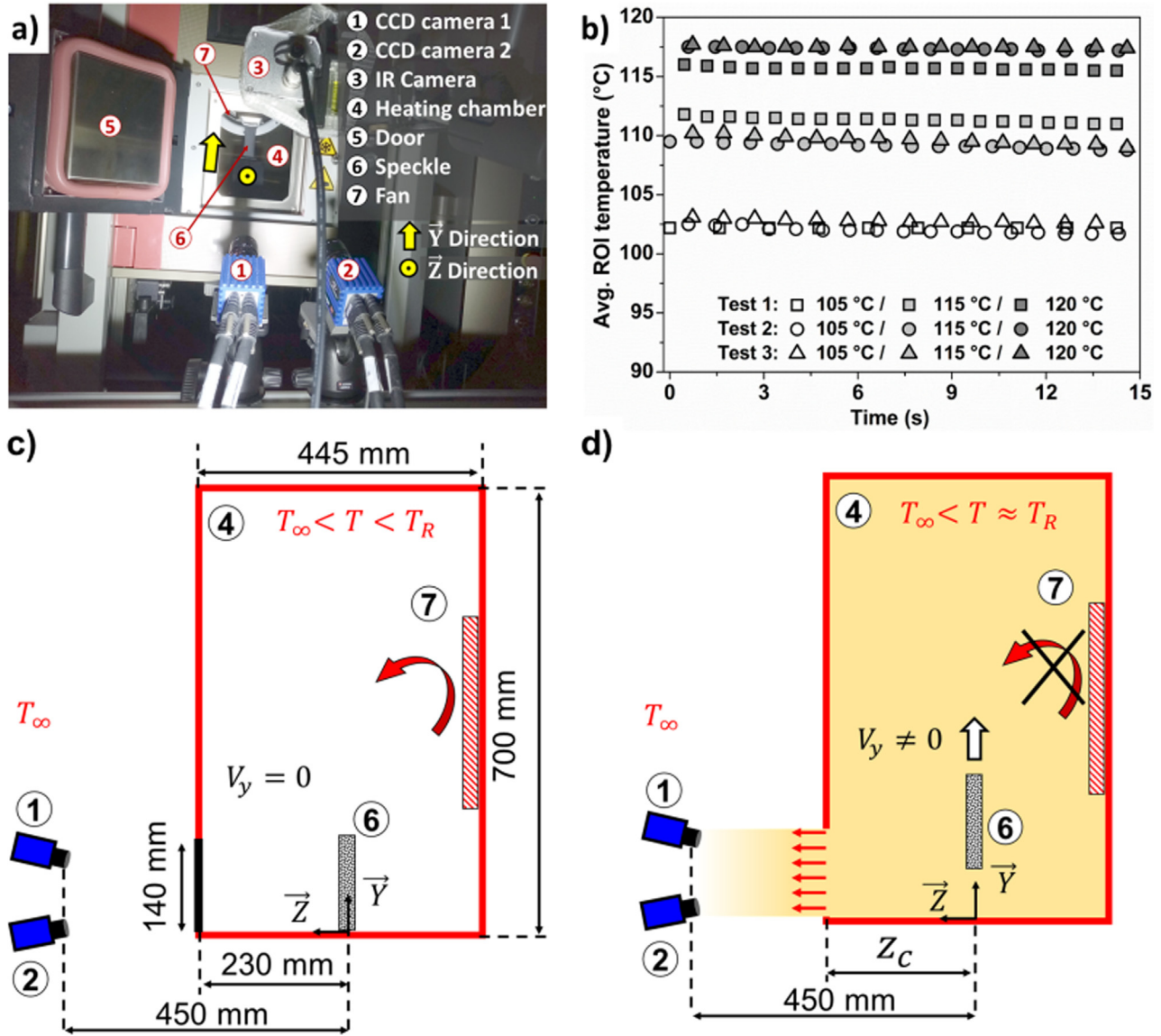


Fig. 1. (a) Experimental equipment. (b) Average temperature at the ROI measured by the IR camera for the same speckled specimen across all tests with varied temperature/speed conditions. (c) Illustration of the sealed thermal enclosure during temperature regulation. (d) Illustration of the partially open thermal enclosure during rigid body motion tests.

analysis of the areas under the curves between t_0 and $t_0 + 15$ s for speeds of 10, 50, and 100 mm/min resulted in algebraic variations of +0.8%, -3.1%, and -2.3% respectively. This quantification confirms that in the absence of heat haze, changes in image intensity remain limited. Upon introduction of heat haze, the most pronounced shifts in pixel intensities towards higher greylevels were observed at 100 mm/min. At 10 mm/min and 50 mm/min, the peak shifting towards higher greylevels seemed to mirror optical distortions introduced by heat haze, with discernible temporal variations. For instance, at 120 °C and 50 mm/min the trend of greylevel variations over time, as depicted in Figure 2b, did not consistently incline towards higher values. The associated algebraic variations of curve areas at $t_0 + 5$ s; $t_0 + 10$ s and $t_0 + 15$ s were of +2.8%, -2.2%, and -6.5% respectively. Upon the conducted thorough histogram

analysis, it is evident that pixel oversaturation did not occur, and changes over time of image intensity remained notably limited. Thus, the influence of the “black body” effect falls beyond the scope of this study. To visually inspect the speckle in presence of heat haze, a few supplementary raw stereo-DIC images are provided in supplementary data. These images correspond to tests conducted at 120 °C with imposed displacement speeds of 10, 50, and 100 mm/min.

2.2.3 Verification of potential effect of applied speckle on emissivity

To assess the potential impact of speckle patterns on emissivity variations, a dual-domain speckle pattern was introduced to a second specimen used only for “non-moving”

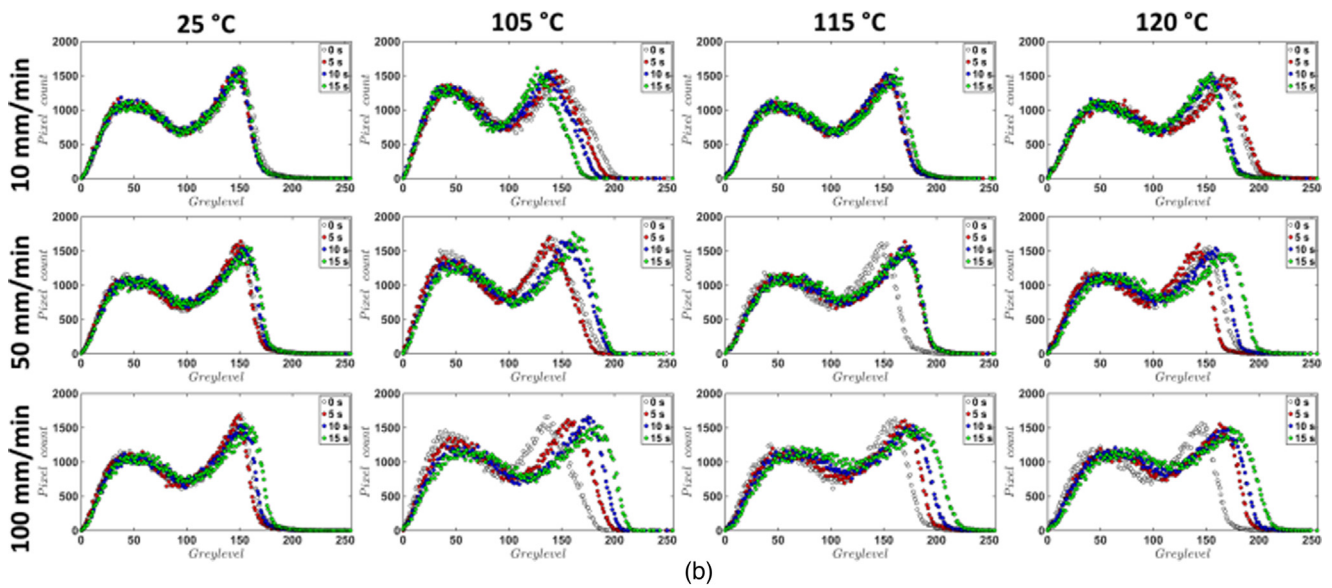
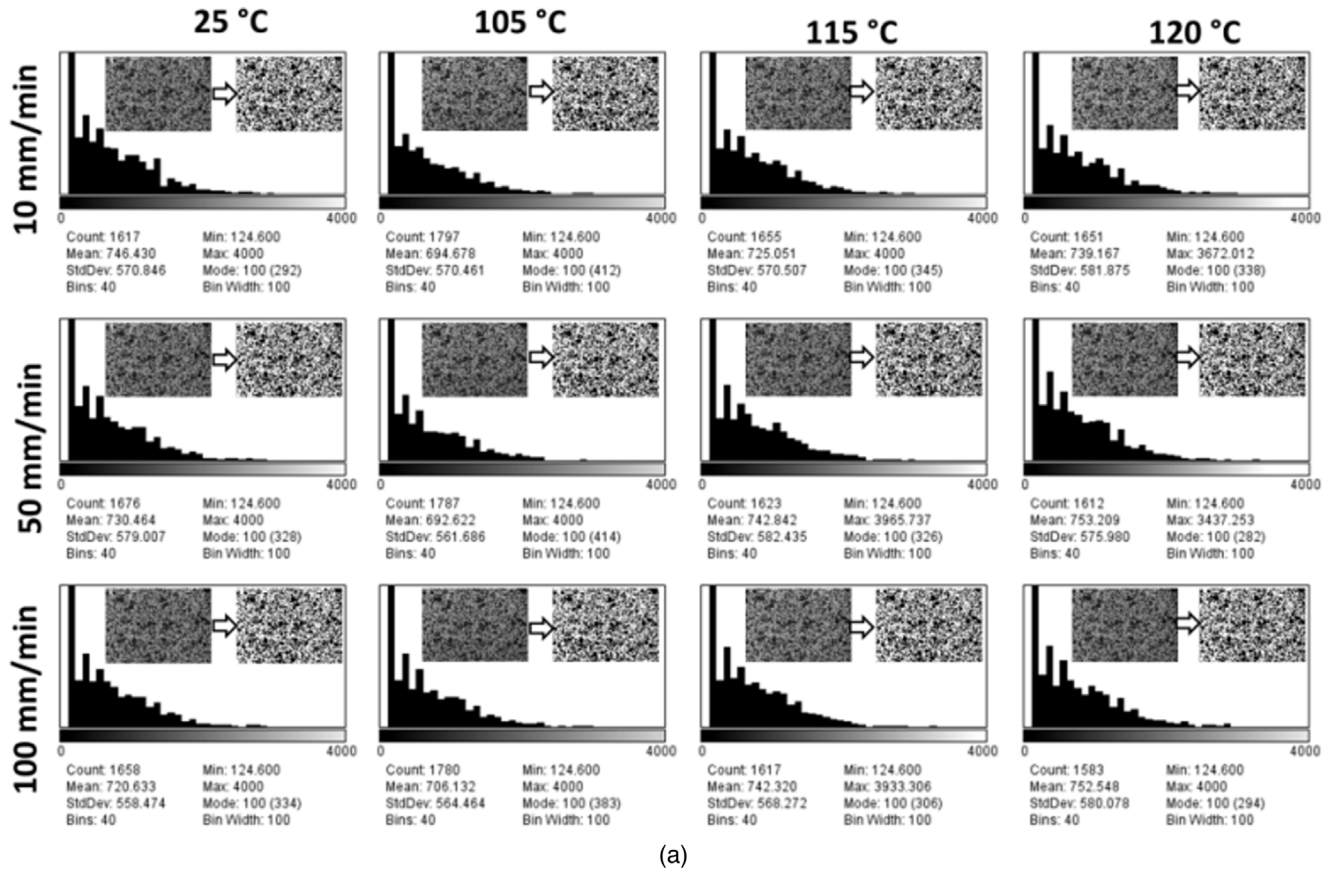


Fig. 2. (a) Feret's diameter distributions of black spots within the considered virtual gauge for stereo-DIC computations. The shown miniaturized images correspond to captured (left) and binarized (right) images of the speckle at time t_0 . All dimensions are presented in micrometers. (b) Histograms of greylevels from all tests conducted on moving specimen and corresponding to time stamps indicated in the legend.

specimen tests. An illustrative depiction of this dual-domain speckle configuration is provided in [Figure A1](#) in [Appendix A](#). The zones with different black spot densities were termed “Coarse” for low black spots density and “Fine” for the highest density of black spots. The IR camera’s emissivity was deliberately adjusted to unity. Average temperature measurements were acquired from equivalent areas within the speckle domains during “non-moving” specimen tests at temperatures (T_R) of 105 °C and 115 °C. The obtained average temperature profiles are presented in [Figure A2](#) in [Appendix A](#). A temperature difference of less than 1.5 °C was observed between the two speckle domains, with higher temperatures in the denser black spot region. The authors recall that thermograms served as supplementary temperature checks within the speckle and for backing the embedded K -type thermocouple used for regulation of the heating chamber. To minimize speckle effects on the IR camera measurements, the same specimen with the same speckle patterns (which was characterized in [Sects. 2.2.1](#) and [2.2.2](#)) was used consistently for all “moving specimen” tests and emissivity of the IR camera was assumed equal to unity. The study’s systematic approach, utilizing identical speckle patterns, mitigated potential experimental bias related to emissivity changes during IR measurements.

2.2.4 Verification of potential thermal degradation of the speckle

Complementary experimental tests were conducted on the dual-domain speckle (which was indicated in [Sect. 2.2.3](#)) according to the same thermal procedure (as indicated in [Sect. 2.3](#)) to investigate potential thermal degradation of the speckle. The corresponding tests were performed in the case of a “non-moving” specimen at temperatures of 25, 105, 115, and 125 °C. The latter regulation temperature was purposely set 5 °C higher than the one indicated in [Section 2.1](#). Thermal and optical data were collected at time t_0 (after achieving T_R) to assess potential changes in the speckle patterns. Infra-red thermograms were also provided in [Fig. A3](#) in [Appendix A](#) to indicate the average temperature within the region of interest (ROI). Simultaneously, optical images that were captured using the left camera of the stereo-DIC system underwent processing with an Otsu filter of the collected optical images following by an automatic watershed filter. These filters isolated the black spots of the speckle patterns, allowing for a statistical analysis of the Feret’s diameter distribution. The histograms generated from this analysis revealed no significant alterations in the Feret’s diameter (see [Figure. A3](#) in [Appendix A](#)). As the relative errors in Feret’s diameter were less than 1.5 % compared to the speckle at 25 °C, negligible thermal degradation of the speckle was confirmed. This observation aligns with findings by Berny et al. [21], which propose that thermal degradation becomes noticeable at temperatures exceeding 300 °C. The comprehensive complementary analysis provided in [Appendix A](#) supports the assumption that the tested temperature range does not induce substantial speckle deterioration.

2.3 Experimental procedure

Each rigid body test followed these steps: (i) Regulating the thermal chamber, (ii) Stabilizing the temperature (3 min), (iii) Initiating stereovision recordings (5 fps), (iv) Opening the observation door of the thermal chamber, (v) Halting the ventilation of the thermal chamber, (vi) Commencing the rigid body translation, (vii) Halting all systems after CCD cameras’ random memory saturation. It is important to note that the experimental procedure, based on the rigid body motion tests, encompassed three imposed speeds {10; 50; 100} mm/min, four regulation temperatures {25; 105; 115; 120} °C and relied on the same speckled specimen. Tests performed at the same displacement speeds were respectively designated Test1, Test2, and Test3. The various thermal conditions were chosen within the thermoforming temperature range of a commonly used thermoplastic, High Impact Polystyrene (HIPS), based on a prior study by the authors involving an industrial-scale thermoforming equipment [29]. In the heating step of a thermoforming cycle for large thermoplastic sheets, the heated material may display temperature dispersion of up to 15 °C. The chosen regulation temperatures in all cases represented different possible thermal conditions for forming HIPS (with $T_g \approx 96$ °C):

- Case 1: 105 °C ($\approx T_g + 10$ °C) – defined as the minimum.
- Case 2: 120 °C ($\approx T_g + 25$ °C) – defined as the maximum.
- Case 3: 115 °C ($\approx T_g + 20$ °C) – defined as a verification case.

Due to the random nature of image distortions caused by heat haze, one single rigid body test was considered sufficient for each combination of parameters (speed, temperature). Despite the simplicity of the described experimental protocol, synchronizing measurements across the three systems (tensile machine, thermal chamber, and stereo-DIC system) necessitated additional precautions involving: (i) temperature control during stereovision, (ii) calibration of the stereo-DIC system, and (iii) identification of the reference state of the speckle patterns after temperature regulation. Subsequent paragraphs will provide further details on these technical precautions.

2.3.1 Temperature evolution during stereovision

Verification efforts were centered on the period following the opening of the heating chamber door. This aimed (i) to estimate the required duration for maintaining the temperature above the glass transition of HIPS (96 °C) and (ii) to characterize the temperature of the speckled region of interest (ROI) during stereovision recordings. To prevent significant temperature drop between the beginning and end of optical measurements, all digital image correlation calculations were limited to a duration of 15 s after effective specimen translation commenced (i.e., the global starting point of the experimental timeline denoted by t_0).

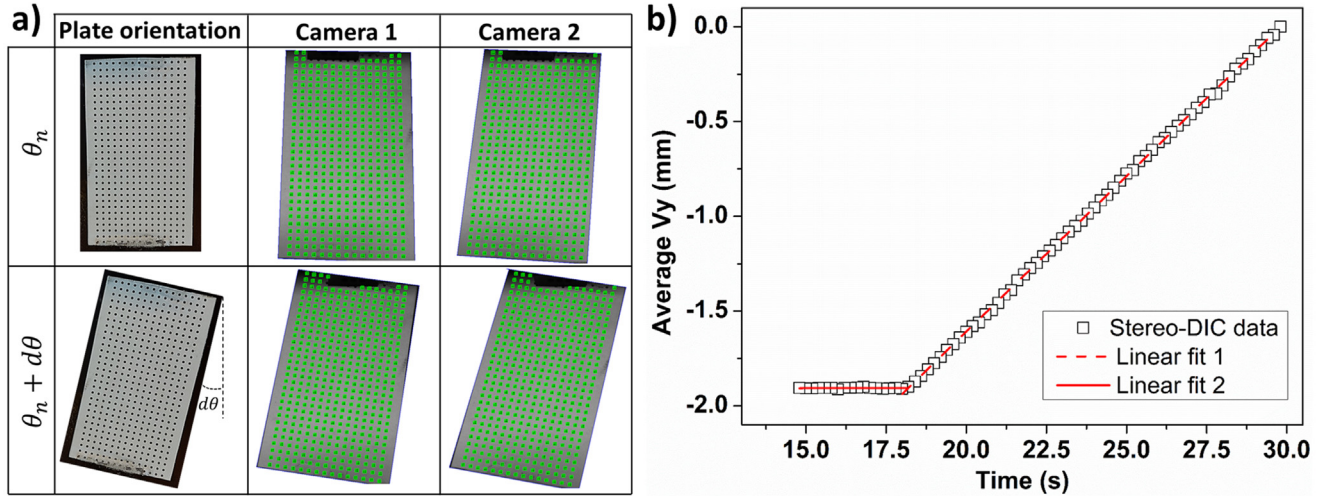


Fig. 3. Illustration of the calibration grid and the corresponding reference markers. (b) Backward double-fit identification of the reference of effective rigid body motions.

2.3.2 Stereo-DIC calibration and post-processing

The calibration of the stereovision system was performed at 25 °C using a grid containing equidistant target points (Fig. 3a). Translations and rotations of the grid were performed in the plane (XY) of the hydraulic jaws of the tensile machine to capture five pairs of images. Utilizing DaVis software (LaVision®) the intrinsic and extrinsic parameters of the stereo-DIC system were identified (Tab. 1). All image correlations considered a virtual gauge covering approximately $35 \times 30 \text{ mm}^2$. The defined extents of the subsets and of the step size were respectively fixed to $19 \times 19 \text{ pixels}^2$ and 9 pixels. Due to the extent of final displacements reached by specimen, an image correlation procedure implemented in DaVis and designated by “sum-of-differentials” was applied. More details about the sum-of-differential procedure can be found in the following reference [3].

Before conducting the digital image correlations, it was necessary to objectively identify the reference state of displacements at t_0 , the moment of effective initiation of rigid body motion, utilizing the sets of recorded stereoscopic images. The method employed to identify the reference image pair at t_0 (i.e., the effective starting point of the experimental timeline) for all three used experimental devices (the tensile machine, the stereo-DIC system, and the IR-camera, as presented in Fig. 1a) was based on a post-processing approach. This approach entailed analyzing the recorded images in reverse order, moving from the end to the beginning. Through a double linear fitting process, the point of intersection of the fitted curves was identified as t_0 . This two-step procedure was applied across all conducted tests within the current study. Figure 2b provides an illustrative example of this method, where negative displacements denote the reversed order post-processing of stereoscopic images. Two distinct domains are distinguishable: (i) the first is a quasi-static domain, representing the time period before the start of effective speckled specimen translation,

and (ii) the second domain corresponding to a quasi-linear displacement increase at a constant slope, indicative of the effective rigid motion along $\vec{Y}$ direction.

2.3.3 Effect of reference state of displacements on statistical data

The influence of the choice of the reference state of the speckle on the statistical data distribution was further investigated at 25 °C (i.e., in absence of thermal haze). Within this context, two reference states were considered: the first reference state (Ref1) was determined using the double regression method (as outlined in Sect. 2.3.2), and the second reference state (Ref2) was chosen visually at the moment of complete opening of the observation window of the thermal chamber.

Image correlation operations were performed on the same set of stereoscopic images corresponding to the rigid body test conducted at 10 mm/min and 25 °C. To visualize the distribution of displacements (V_y), histograms centered around five specific time points were extracted. These time points were defined at 1, 2, 3, 4, and 5 s from Ref1 and Ref2, respectively. In the case of Ref1 (Fig. 4a), the spatial distribution of centered displacements appeared to obey a single Gaussian distribution. However, for Ref2 (Fig. 4b), the centered histograms indicated the presence of at least two types of displacements within the same region of interest (ROI). Further visual examinations of the recorded stereoscopic image pairs confirmed that at the moment the chamber window was opened and before the onset of rigid body translation, the ventilation fan was not completely stopped. As a result, the second observed population of displacements was generated by the image correlation algorithm due to changes in light reflection caused by the fan blades. The deceleration of the ventilation fan’s blades is clearly discernible from the attenuation of the left-side peaks over time in

Table 1. Intrinsic and extrinsic parameters obtained from calibration of the stereo-DIC system.

Parameters	Cam. 1	Cam. 2
Rotations (°)	37.034, −2.979, −2.157	36.014, 6.378, −0.854
Positions (mm)	−14.246, −195.191, 645.764	−22.327, −192.428, 653.943
Focal length (mm)	43.158	43.340
Scale factor (pixel/mm)	11.151	

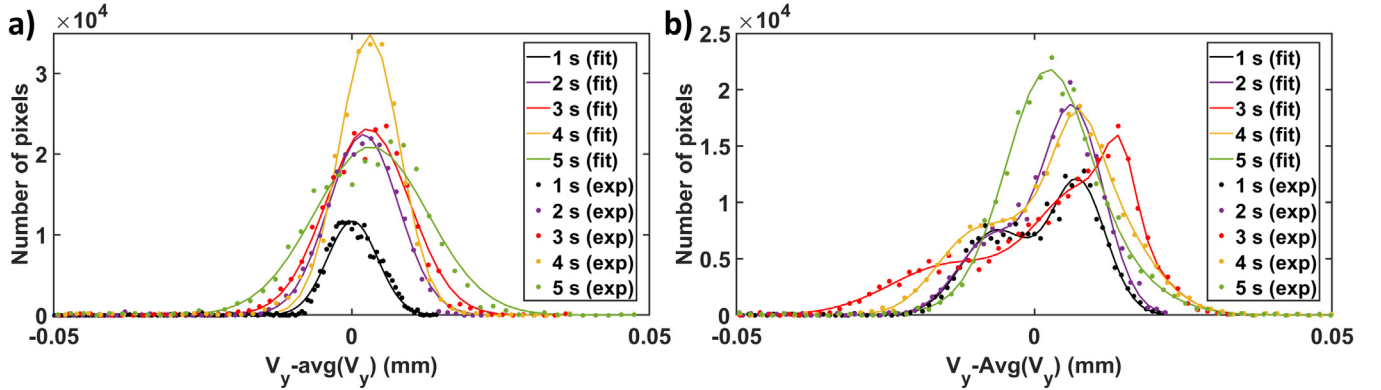
**Fig. 4.** Histograms of centered V_Y corresponding to Ref1 (a) and Ref2 (b).

Figure 4b. Given the challenges associated with visually selecting the reference state after thermal regulation, the double regression method was adopted to quantitatively assess the errors induced by heat haze, as will be elaborated in the subsequent sections.

2.3.4 Inertial effects of the tensile machine

To assess the characteristic time-response of the tensile machine required to initiate effective motion of the speckled plate, imposed displacements (V_Y^*) were extracted from the cross-head's movement along the $\vec{Y}$ direction using the control interface at {10; 50; 100} mm/min. Subsequently, the corresponding derivatives over time (dV_Y^*/dt) were calculated. As observed from Figure 5a, the change in speed slopes took almost 0.4 s to manifest. This time-offset was implicitly considered to define t_0 from the imposed displacements recorded by the tensile machine.

2.4 Thermal problem: Natural convection near partially-open vertical cavity

Considering the adiabatic temperature chamber's capacity to minimize convective air currents within the specified temperature range, the thermal problem during stereoscopic recordings was framed as a scenario involving a partially-open vertical enclosure. This setup was achieved by opening the 9.2 area % observation window (Fig. 1c), paralleling the concept of a partially-open cavity discussed in references [30,32]. According to the first law of thermodynamics, the established temperature difference

($\Delta T = T_R - T_\infty$) caused natural convection, leading to the bulk motion of air molecules from the enclosure's interior to the exterior (Fig. 1c). Zhao's unified formalism [33], applied to natural convection in compressible fluids without the influence of forced air velocity, correlated the emergence of a convective heat flux (q) with localized changes in air density (ρ) along the $\vec{Z}$ direction, as expressed in equation (1). Due to the relatively lower density of heated air compared to the external air, buoyancy-driven thermal plumes (i.e., resembling feather-shaped streams) were expected to rise against gravity with a deviation along the $\vec{Z}$ direction [34].

$$q = \frac{\rho c_p}{\beta} \left[\alpha \frac{\partial \ln \left(\frac{\rho}{\rho_\infty} \right)}{\partial z} \right] \quad (1)$$

where, a is thermal diffusivity, β is volumetric thermal expansion, ρ_∞ is air density at temperature T_∞ and C_∞ is specific heat capacity.

2.4.1 Turbulence of a natural convective flow

To assess the turbulence in the natural convection of air, the dimensionless Rayleigh number (Ra) was calculated as expressed in equation (2). In this equation, Ra represents the ratio of buoyant forces causing instability to diffusive restoring forces, thus indicating the onset of natural convection.

$$Ra = \frac{g \beta z_c^3}{\alpha \nu} (T_R - T_\infty), \quad (2)$$

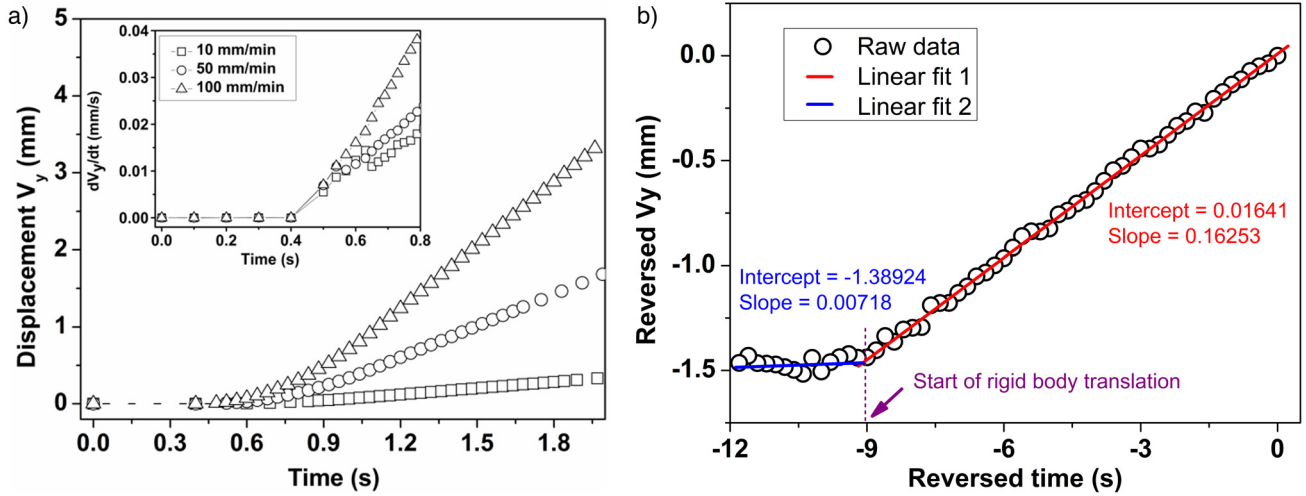


Fig. 5. (a) Imposed displacements (V_y^*) and their derivatives (dV_y^*/dt) from tensile machine. (b) Double-fit based identification of t_0 origin of time from the test case conducted at 105 °C and 10 mm/min.

where, the indicated physical parameters and their respective corresponding values are provided in Table B1 (Appendix B), while the critical distance z_c (Fig. 1c) separates the speckle (at T_R) from the surrounding environment (at T_∞). With the imposed temperature T_R falling within the range of [105;120] °C, the corresponding Ra numbers were situated within the interval of $[9.8 \times 10^7; 1.2 \times 10^8]$. These values closely aligned with the threshold for the onset of turbulence (i.e., $Ra = 10^8$ in the natural convection of air, as can be verified from literature [24,35]).

2.4.2 Thermal performance of the temperature chamber

For the tests conducted at T_R , of 105, 115, and 120 °C, the chamber's temperature (T) and the average temperature of the speckled specimen (T_s) were monitored upon opening the observation window to assess their stability (Fig. 1c). According to Figure 1b, the average temperature (T_s) was lower than T_R by almost five degrees Celsius. This difference can be attributed to the control mechanism of the temperature regulation utilizing an integrated K -type thermocouple in contact with the inner wall of the temperature chamber and located far from the speckled plate. However, the non-overlapping profiles of T_s (Fig. 1b) across different imposed T_R levels indicated that the used equipment allowed for the generation of relatively controlled specimen temperatures.

2.5 Optical problem: domain affected by natural convective flow

The provided formalism aims to estimate bias errors (Δy) in the presence of heat haze in the air. It was formulated based on the work of Dalziel et al. and Fermat's principle

regarding the propagation of light rays in media with heterogeneous refractive indices [36,37]. In comparison to similar formalisms outlined in [20,25], the current study considers the generation of turbulent natural convection between a speckled surface at T_R and cameras maintained at T_∞ in the context of a partially open vertical enclosure. As illustrated in Figure 6, one ray of light was considered and was assumed parallel to $\vec{Z}$ direction (i.e., $\frac{dy}{dz} = \tan(\alpha) \ll 1$). In addition, spatial variations of the refraction index of air n^* from its reference value n_∞ (at T_∞) were assumed of same magnitudes along all spatial directions as expressed by equation (3):

$$n^* = n^*(x, y, z) = n(x, y, z) - n_\infty. \quad (3)$$

Based on the variational principle for the behavior of light in an inhomogeneous medium [36] and assuming $n^* \ll n_\infty$, the deviation of the trajectory of the light ray can be expressed by equation (4):

$$\frac{d^2 y}{dz^2} = \frac{1}{n_\infty} \frac{\partial n^*}{\partial y}. \quad (4)$$

By recalling that $\frac{dy}{dz} = \tan(\alpha)$ and assuming that the respective angular trajectories of light a_1 and a_2 in Figure 6 were equal, the integration of equation (4) over the heat-affected-domain ($z \in [z_c; z_c + z_i]$) satisfied equation (5):

$$\tan(\alpha_2) = \tan(\alpha_0) + \frac{1}{n_\infty} \int_{z_c}^{z_c + z_i} \left(\frac{\partial n^*}{\partial y} \right) dz. \quad (5)$$

Based on a geometric interpretation (Fig. 4), bias error Δy can be expressed by equation (6):

$$\Delta y = y_i - y_0 = z_c [\tan(\alpha_1) + \tan(\alpha_2)] \approx 2z_c \tan(\alpha_2). \quad (6)$$

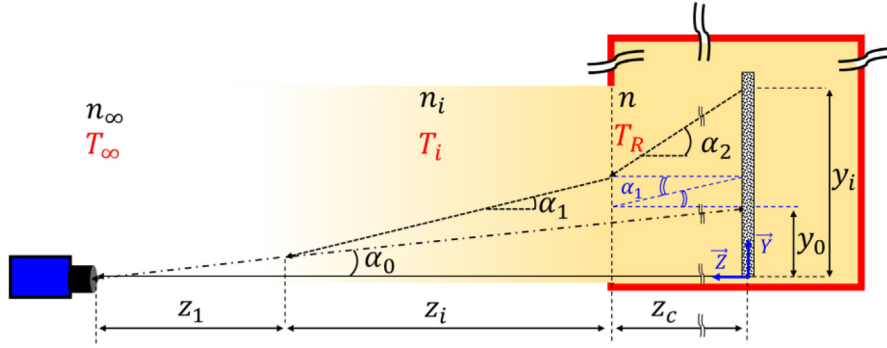


Fig. 6. Schematic illustration of the optical problem presented in case of one single camera of the stereoscopic system.

By combining equations (3) and (6), and recalling that $\lim_{\alpha_0 \rightarrow 0} [\tan(\alpha_0)] = 0$, the bias Δy can be expressed by equation (7):

$$\Delta y \approx 2z_c \frac{1}{n_\infty} \int_{z_c}^{z_c+z_i} \left(\frac{\partial n^*}{\partial y} \right) dz. \quad (7)$$

Based on the empirical equations of C eddor [20,38], refraction index of the air (n^*) within the range of $[20;150]^\circ C$ can be approximated to $m \cdot T$ (where m is a fitting constant). Consequently, Δy can be expressed in terms of local thermal differential as indicated in equation (8):

$$\Delta y \approx z_c \frac{m}{n_\infty} \int_{z_c}^{z_c+z_i} \left(\frac{\partial T}{\partial y} \right) dz. \quad (8)$$

By assuming that $z_1 + z_i \approx 0.22$ m, $z_c = 0.23$ m and the temperature difference $\Delta T \in [80;95]^\circ C$ across a field of view of 0.04 m in height, Δy ranged between 58.4 and 69.4 μm . For a pixel size of 5.5 μm , these bias errors corresponded to a range of $[10.6;12.6]$ pixels which were 10^3 higher than sub-pixel noise levels expected at precise laboratory-scale DIC measurements.

2.6 Statistical analyses of temporal random errors and bias errors

2.6.1 Assumptions for statistical analyses

In conformity with the formalism provided by Su et al. [18], a recorded optical image (I) of the speckle can be presented by a discrete function $F(x,y)$ of a finite resolution, such as $I = F(x,y)$. This same image (I) can be associated to its antecedent in the real world (I_0) as expressed by equation (9):

$$I = G \cdot I_0 + W \quad (9)$$

where, G encodes optical distortions caused by heat haze and W encodes optical noise from sensors. By considering a reference pattern $p(x_0, y_0)$ in the real world, a rigid body translation of the specimen (along $\vec{Y}$ direction) at a

distance y_k results in a target pattern $p(x_0, y_0 + y_k)$. By assuming that stereo-DIC calibration minimized noise ($W_k \approx W$), a reference image $F(x_0, y_0)$ and a target image $F(x_0, y_0 + y_k)$ both affected by random optical distortions (G_k) due to heat haze can be expressed by equation (10):

$$\begin{cases} F(x_0, y_0) \approx G_0 \times p(x_0, y_0) + W \\ F(x_0, y_0 + y_k) \approx G_1 \times p(x_0, y_0 + y_k) + W \end{cases} \quad (10)$$

Based on the decomposition indicated in equation (10), and by recalling that stereo-DIC displacements (V) were identified based on a minimization process of the sum of squared difference criterion (cf. Sect. 2.5) as expressed in equation (11), bias errors representing the deviation of measured displacements from imposed ones were considered random.

$$BEr(t)_{|thermal} = BEr(t)_{|@T_R} - BEr(t)_{|@25^\circ C} | t \in [1, \dots, 75] \quad (11)$$

Due to randomness of displacement bias, statistical analyses of displacement components, errors and uncertainties were considered global and relied on the evaluation of respective mean and the standard deviation as defined in equations (12) and (13):

$$\sigma_k \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_{i,k} - \bar{x}_k)^2} \quad (12)$$

where $\bar{x}_k$ is the spatial mean value over the ROI of the component x_k of a displacement vector ($V_X; V_Y; V_Z$) measured at a time increment k .

$$\bar{x}_k = \frac{1}{N} \sum_{i=1}^N x_{i,k} \quad (13)$$

At $25^\circ C$, spatial random errors, temporal random errors and relative uncertainty were evaluated based on the deviations of displacement components from imposed displacements (V_X^*, V_Y^*, V_Z^*) to assess the baselines of noise. In presence of heat haze (i.e., at $T_R \neq 25^\circ C$), the corresponding values were evaluated from the deviations between measured displacement components and their

baselines measured at 25 °C. Bias errors caused by heat haze were evaluated by assuming additive decomposition of displacements as indicator of required displacement corrections over time.

2.6.2 Measurement quality: Systematic error and Relative uncertainty

Systematic errors and precision of measurements were respectively evaluated by quantifying mean bias errors and relative uncertainty over time in the presence of heat haze. Within this study, the quantification of precision and errors for stereo-DIC was focused on the V_Y components of displacement vectors. The focus primary emphasis was mainly attributed to the evaluation of the temporal random errors ($TStdev V_i$) as expressed in equation (14) and bias errors $BEr(t)$ as expressed in equation (15). The reader can refer to the following references to have more insight about the evaluation of noise and systematic errors from stereo-DIC measurements [8,9].

2.6.3 Temporal random errors

Temporal standard deviation $TStdev(V_i)$ referring to the temporal variation in the deviation of each displacement component ($V_i(n, m) - V_i^*(n, m)$) over across the entire duration of the rigid body test at the same subset center of coordinates (n,m) within the ROI. $TStdev(V_i)$ in the main directions ($\vec{X}, \vec{Y}, \vec{Z}$) were evaluated as in equation (14) to generate full-fields of localized temporal noise:

$$TStdev[V_i(n, m)] = \sqrt{\frac{1}{T} \sum_{t=1}^T [(V_i(m, n, t) - V_i^*(t)) - \frac{1}{T} \sum_{t=1}^T (V_i(m, n, t) - V_i^*(t))]^2} \quad (14)$$

where, T , $V_i(n, m)$ and $V_i^*(t)$ correspond respectively to the total time increments ($T=75$), the measured and imposed displacement components at a time increment (t).

Given the same temperature/speed couple of parameters, the reconstructed fields of temporal random errors were needed not only to quantify levels of temporal noise but also to visualize regions with accumulated major optical distortions caused by heat haze.

2.6.4 Mean bias error

Mean bias errors (i.e., representing systematic errors) were assessed following a methodology akin to that described by Pan et al. [39], as outlined in equation (15). This procedure was then extended to each time increment between t_0 and a defined time stamp.

$$BEr(t) = \left[\frac{1}{N \times M} \sum_{n,m=1}^{N,M} (V_i(n, m, t) - V_i^*(t)) \right]_t \quad (15)$$

where, N and M are respectively the total numbers of subset centers along the $\vec{X}$ and $\vec{Y}$ directions of the ROI.

3 Results and discussion

3.1 Principal components of displacement vectors

3.1.1 Baselines of measured displacements

• Case of the moving specimen

At 25 °C and in the absence of any heat source in the optical field of the stereoscopic system, displacement components ($V_i; i \in \{X, Y, Z\}$) from all conducted tests at different speeds were measured. The first measured displacement vectors were obtained from the corresponding test at a time-stamp of 15 s. Subsequently, statistical analyses of means ($V_i; i \in \{X, Y, Z\}$) and standard deviations ($\sigma_i; i \in \{X, Y, Z\}$) of principal components of the measured displacement vectors (V_i where $i \in \{X, Y, Z\}$) over the considered region of interest were extracted and plotted in Figure 7. In terms of precision, the Y -direction corresponds to the translation direction imposed by the tensile machine (see Fig. 1), while the $\vec{Z}$ direction corresponds to the out-of-plane direction (see Fig. 1a). The time evolution of V_X and V_Z components was examined to check the presence of any potential non-imposed displacements (i.e., parasite displacements) in transverse directions. At 25 °C, the profiles of V_Z in Figure 7 presented the baselines of mean displacements, offering insight into the effective translations measured in the absence of heat haze. Specifically, at speeds of 10, 50, and 100 mm/min, the V_Y baselines (Figs. 7b, 7e, and 7h) displayed quasi-linear increases over time with slopes of 9.8, 49.5, and 98.9 mm/min- respectively. For the imposed speed of 10 mm/min, the V_x and V_Z baselines in Figure 7a and Figure 7c were nearly aligned with their respective zero lines (i.e., $V_Z=0$). At 50 mm/min (respectively 100 mm/min), parasite displacements V_X and V_Z became evident in Figures 7d Figure 7f (respectively in Fig. 7g), displaying quasi-linear progressions and reaching approximately -0.2 and 0.7 mm (respectively around -0.45 and 1.7 mm) at a time-stamp of 15 s. Such evolution of both transverse components indicated existence of a non-visual misalignment of the speckled plate around the $\vec{Y}$ and $\vec{X}$ directions due to experimental bias induced by the clamping configuration of the experimental equipment. This considered experimental assumption is the most probable according to experimental verifications related to speckle characterizations indicated in Section 2.2.

• Case of a non-moving specimen

Supplementary verification experiments were systematically executed on a “non-moving” specimen to comprehensively elucidate: (i) stereo-DIC equipment performance at 25 °C, (ii) image correlation method precision at 25 °C, and (iii) the scope of measured displacements amid heat haze. The procedures encompassed a second calibration of the stereo-DIC system using uniform illumination and the same reference plate. Calibration data from both the initial

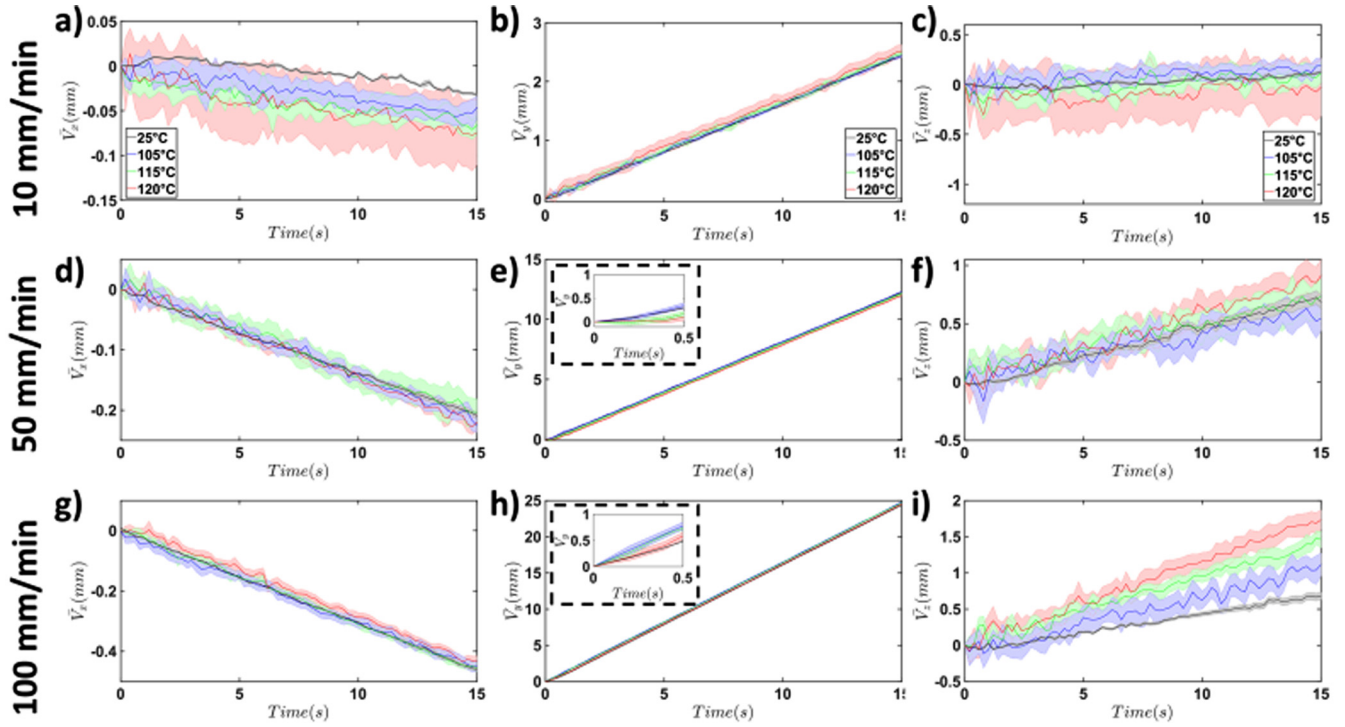


Fig. 7. Time evolution of means (continuous lines) and standard deviations (background bands) calculated from displacement components measured by stereo-DIC at considered regulation temperatures and speeds. The average displacement components are quantified in millimeters.

and subsequent campaigns were integrated and are accessible in Table C1 in Appendix C. The specimen remained stationary and underwent testing at temperatures of 25, 105, 115, and 125 °C. Notably, the highest regulatory temperature (T_R) was intentionally set 5 °C higher than that detailed in the campaign described in Section 2.3. This modification was tolerated to qualitatively assess calibrated stereo-DIC system performance in the case involving heat haze presence and absence. Employing the same post-processing approach, baselines were calculated via the “sum of differential” image correlation method. Detailed baseline outcomes are provided in Figure C1 in Appendix C. At a temperature of 25 °C, where heat haze is absent, the baselines derived from the “non-moving” specimen demonstrate centered displacement components, spanning the entire 15 s timeline while closely aligning with the zero line. The mean measured displacements over this period ($V_X = -0.682 \times 10^{-3}$ mm, $V_Y = 0.721 \times 10^{-3}$ mm and $V_Z = 6.00 \times 10^{-3}$ mm) exhibit one order of magnitude between in-plane and out-of-plane precisions, as indicative of the optical equipment’s performance of the used Stereo-DIC system. The standard deviations along the principal directions, namely X , Y and Z , remain consistently constrained. Moreover, a thorough observation of the generated baselines throughout the 15 s duration at 25 °C reveals no discernible alterations attributed to the image correlation procedure. With an increase in the regulation temperature (T_R) to 105, 115 and 125 °C, the average displacement data exhibit noticeable shifts away from the zero line. These shifts

are observed to be randomly positioned both below and above the zero line, displaying occasional fluctuations over time, as depicted in the temporal evolution within Appendix C. Such behavior reflects the random optical shimmering caused by the turbulent nature of heat haze effect. An important observation arises from the average displacements in the principal directions, which are detailed in Figure C2 in Appendix C. Particularly under the influence of heat haze, the magnitudes of displacement shifts exhibit an amplification of over one order of magnitude. Notably, the measured displacements from the “non-moving” specimen along the Z direction exceed those of the other directions. For example, at 115 °C, V_Z reaches approximately 170.9×10^{-3} mm, a contrast to the 6.0×10^{-3} mm measured at 25 °C. In comparison, at the same temperature, V_X and V_Y reach 9.7×10^{-3} mm and -29.6×10^{-3} mm, respectively, compared to the 0.61×10^{-3} mm and the 0.72×10^{-3} mm at 25 °C. This pronounced discrepancy underscores the substantial impact of heat haze on displacement measurements, with the Z direction demonstrating heightened susceptibility to this influence.

3.1.2 Measured displacements in presence of heat haze

In the presence of heat haze, as T_R increased from 105 to 115 and then to 120 °C, similar slopes were observed in the V_Y profiles (Figs. 7b, 7e, and 7h), accompanied by an increase in the corresponding standard deviations. These augmented dispersions indicated heightened

turbulence of air over the ROI, a phenomenon corroborated by the Rayleigh numbers (*cf.* Sect. 2.3). For a fixed T_R , the width of standard deviation bands (Fig. 7) exhibited minimal expansion over time, leading to the assumption that cumulative errors stemming from the image-correlation procedure were relatively negligible in comparison to those induced by heat haze. The average transverse components of parasite displacements V_X and V_Z displayed not only heightened standard deviations but also deviations from their respective baselines recorded at 25 °C (Fig. 7a-7c and Figs. 7g-i). With increasing speed from 10 to 50 mm/min (and further to 100 mm/min), the standard deviation bands narrowed, particularly evident for a T_R of 120 °C (Figs. 7e-7f). For instance, at a time-stamp of 9 s, σ_z at 50 mm/min accounted for 57.1 % of that measured at 10 mm/min. In summary, inspection of measured displacement components in the presence of heat haze indicated: (i) the capacity of the temperature chamber to induce heightened dispersions of displacements within the range of thermoforming temperatures and (ii) the existence of parasite effects in the out-of-plane $\vec{Z}$ direction attributed to potential existence of experimental bias. With increasing imposed speed, these dispersions were attenuated across all principal directions, reflecting increased optical shimmering and consequent heightened filtration of random optical distortions.

3.2 Local deviations of surface angle to out-of-plane axis

As the material of the speckled plate was chosen for its dimensional stability in the range of considered T_R (*cf.* Sect. 2.1), the focus was attributed to mapping local out-of-plane angular deviations of the surface. This was done to confirm the 3D nature of optical shimmering in recorded images and thus validate the need for stereo-DIC over two-dimensional DIC. As the heat flux from natural convection would be most significant at t_0 , Figure 8 presents full fields of angular deviations to $\vec{Z}$ direction (i.e., out-of-plane direction) during the initial 0.2 s of each conducted rigid body translation along the $\vec{Y}$ direction. For pure illustrative purposes, the authors provided two cases at speeds of 10 and 50 mm/min, depicted in Figure 8 at a time stamp of 9 s. At 25 °C, the average angular deviations of the surface for speeds of 10 and 50 mm/min were approximately 2.61° and 2.52°, respectively, with localized maxima reaching 5° (Figs. 8a and 8e). In addition, the projections of displacement vectors on the XY plane (indicated by arrows in Fig. 8) were aligned with the $\vec{Y}$ direction. With the presence of heat haze, Figures 8b-8d and Figures. 8f-8h displayed feather-shaped zones with localized maxima of angular deviations surpassing 10°. These markers indicated regions of significant optical distortions. The most pronounced angular deviations occurred at a T_R of 120 °C, compared to 115 and 105 °C,

reflecting increased turbulence within the range of considered temperatures. As T_R increased, the corresponding projections of displacement vectors on the XY plane indicated not only an increase in magnitudes but also higher in-plane deviations from the $\vec{Y}$ direction. These heterogeneous and localized changes in projected displacement vectors and out-of-plane angular deviations confirmed generation of buoyant heat plumes and, thus delineating zones of major optical shimmering within the range of thermoforming temperatures.

3.3 Temporal random errors (Noise)

3.3.1 In absence of heat haze

Full-field temporal random errors $TStdev(V_i)$ were computed using Eq. 14 over a 9 s period for both speeds of 10 and 50 mm/min, with the results presented in Figures 9 and 10, respectively. At 25 °C, the baseline levels of temporal noise, collected from the case of the moving specimen, exhibited a descending order of magnitude along the $\vec{Z}$, $\vec{Y}$ and then $\vec{X}$ directions. The respective mean values $TStdev(V_i)$ were equal to $24.4 \mu\text{m} > 17.1 \mu\text{m} > 5.8 \mu\text{m}$ at 10 mm/min, and were respectively equal to $135.0 \mu\text{m} > 11.3 \mu\text{m} > 1.4 \mu\text{m}$ at 50 mm/min.

As the speed increased from 10 to 50 mm/min, the observed 553% increase in $TStdev(V_Z)$, can be mainly explained by the detected experimental bias resulting from the plate's clamping configuration. This bias is evidenced by the measured average displacements. Such experimental bias is also apparent from gradient-like effects across over $TStdev(V_i)$ fields obtained along the $\vec{Y}$ and $\vec{Z}$ directions (Figs. 9 and 10, at 25 °C). To further investigate the potential impact of experimental bias associated with increased speed on temporal standard deviations, a straightforward approach was employed. This method involved considering two scenarios wherein artificial parasitic displacements (along the $\vec{Z}$ direction) were assumed to take place due to parasitic bending induced by the clamp which caused small (either positive/negative) bending of the rigid XY plane around the $\vec{X}$ axis (refer to Figs. D1a in Appendix D). Then, the full-fields of ($TStdev(V_Z)$) at 25 °C which were already provided in Figures 9 (at 10 mm/min) and 10 (at 50 mm/min) were re-evaluated according the two following scenarios:

In the first scenario, an artificially imposed out-of-plane displacement bias exhibits a negative slope over time as illustrated in the Figure D1c in Appendix D. The re-evaluated temporal standard deviations, when contrasted with the original experimental data, appear to maintain the same localizations of high and low value albeit with a rescaled representation. Upon transitioning from a speed of 10 to 50 mm/min, there is an observable expansion in the range of temporal standard deviations (refer to Fig. D2 in Appendix D). In the second scenario, an artificially imposed out-of-plane displacement bias with a positive slope over time is considered as illustrated in the

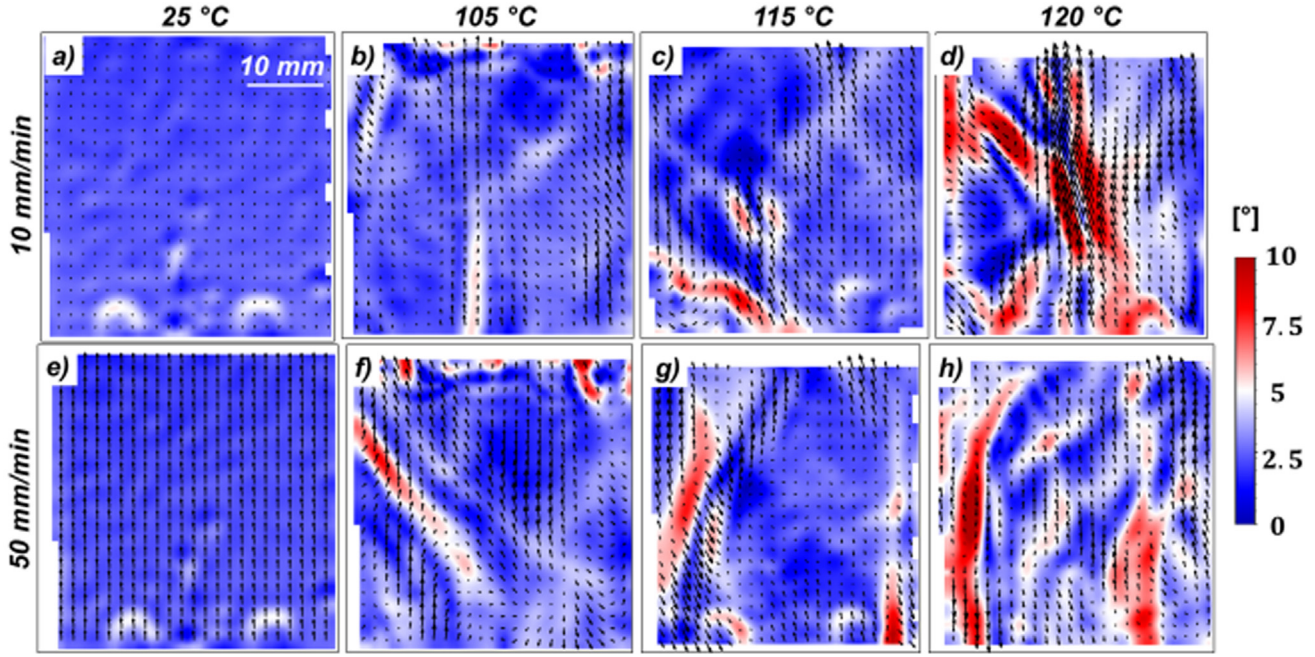


Fig. 8. Full-fields of surface angles to $\vec{Z}$ direction at a time stamp of 0.2 s extracted from all conducted rigid body tests. Black arrows indicate in-plane projections of measured displacements.

Figure D1b in Appendix D. The re-evaluated temporal standard deviations, in comparison to the initial experimental data, appear to invert the positions of high and low values. Notably, with the increase in speed from 10 to 50 mm/min, the range of temporal standard deviations seems to be dampened, suggesting that the artificially imposed slope compensates for the initial experimental bias (refer to Fig. D2 in Appendix D). Both scenarios can further justify that experimental displacement bias can affect temporal standard deviation as the speed increases.

3.3.2 In presence of heat haze

Figures 9 and 10 showed higher maximum temporal random errors localized within feather-shaped zones mainly oriented along the $\vec{Y}$ direction (i.e., the pure translation direction). For the same T_R values, these zones coincided spatially within the same regions within the ROI, while demonstrating an incremental shift towards higher levels among, $TStdv(V_Y)$ and $TStdv(V_Z)$.

In Figure 10, the $TStdv(V_Z)$ fields corresponding to the presence of heat haze unexpectedly showed local attenuation of temporal noise levels when compared to those measured at 25 °C. Such observation seemed to go along with the hypothesis that the cumulative effect of increasing speed in the presence of heat haze tends to filter out random errors over time. Furthermore, by comparing $TStdv(V_Z)$ full fields among 105, 115, and 120 °C, this filtering effect along the $\vec{Z}$ direction seemed to be affected

by the randomness over time of optical shimmering attributed to turbulence from heat waves. Importantly, this phenomenon was not limited solely to the imposed T_R .

3.4 Time evolution of bias errors (systematic errors)

The time evolution profiles of displacement bias from all tests are presented in Figure 11a. All profiles seem to obey to quasi-linear regression functions. In the absence of heating, the bias-error curves exhibit negative slopes for all tested displacement speeds, indicating an underestimation of the measured stereo-DIC displacements. Moreover, these systematic errors become more significant as the imposed displacement speeds increased. Indeed, the absolute values of the corresponding slopes rise from 6×10^{-3} to 28.8×10^{-3} and further to 51.1×10^{-3} . By recalling that the number of numerical correlation operations is fixed to 75 iterations, it should be noted that this effect can be attributed to (i) the respective translation deviations of 0.16, 0.83, and 1.67 mm between the respective image pairs and to (ii) an accumulation of computational errors induced by the used correlation method. Under the effect of heat haze, the slopes of the measured displacement bias profiles exhibit a decrease as they approach the zero line, compared to the cases at 25 °C. Indeed, for speeds of 10 and 50 mm/min, the rise in temperature from 105 to 115 and 120 °C appears to shift the evolution of the bias errors toward positive values. However, this observation does not hold true for a speed

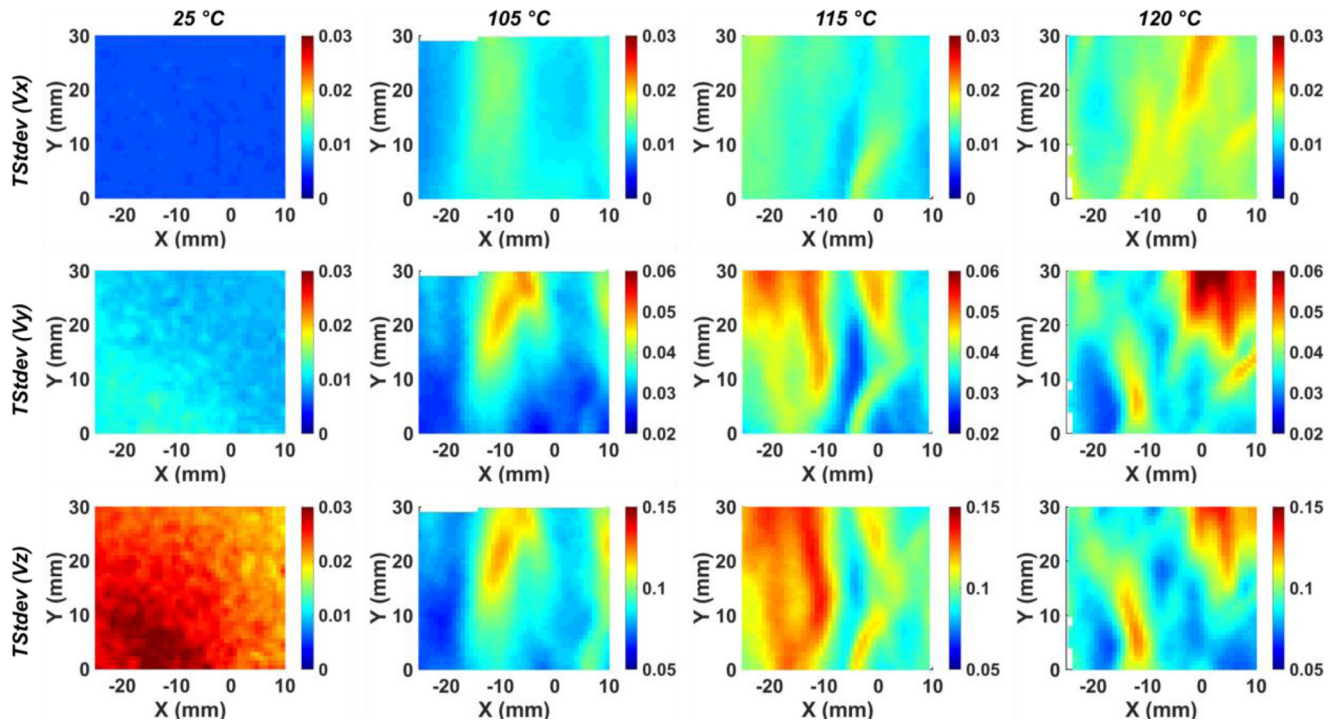


Fig. 9. Full fields of temporal standard deviations (TStdv maps) evaluated from tests conducted at 10 mm/min at a time stamp of 9 s.

of 100 mm/min particularly at 115 and 120 °C. Such irregular changes do not seem to be solely related to optical distortions induced by the natural convection of air; they also seem to be associated with the onset of local turbulence of hot air at the interface of the moving specimen at 100 mm/min.

3.5 Temporal filtering of bias errors

As per the considered experimental protocol, the global bias of the measured displacements can be broken down into two additive components: (i) systematic errors arising from the image correlation method in the absence of heat haze and (ii) systematic errors resulting from heat haze. The output results of thermally induced systematic errors are provided in Figure 11b. The obtained outcomes reveal that the time-evolution of haze-induced errors follows quasi-linear patterns with positive slopes. These corresponding linear regression curves can be considered as corrective functions for thermally-induced systematic errors.

3.6 Case application of temporal filtering of systematic errors

Based on the previously established bias corrective functions, it became feasible to define a temporal correction procedure aimed at mitigating the impact of heat haze. To illustrate this correction procedure, a time stamp at 15 s was chosen from the displacement data of the rigid body motion test conducted at 120 °C and a speed of 50 mm/min.

Initially, the displacement imposed by the tensile machine was extracted from the stereo-DIC displacements to evaluate the spatial distribution of global bias errors (Fig. 12). Subsequently, the bias errors estimated at 25 °C and 50 mm/min for the same time stamp were subtracted. The histograms of displacements corresponding to the outputs of both preceding operations are depicted in Figure 12, and their respective mean displacement values equate to 11.839 and 12.588 mm.

Finally, by additionally subtracting the thermal haze amount using the corrective function corresponding to the specific test conditions (120 °C and 50 mm/min), the mean displacement value shifted to 12.134 mm. Prior to any correction, the displacement error accounted for 5.29 % of the imposed displacement. After conducting the aforementioned filtering operation, the relative error was reduced to 2.23 %, signifying an approximate gain of 44.6 %.

3.7 Limitations of suggested temporal filtering of bias errors

This research addresses the absence of explicit quantitative studies on heat-induced errors and their variations within the thermoplastic thermoforming community. The monitoring of measurement accuracy under realistic conditions holds significant importance. The proposed corrective functions account for systematic errors arising from the image correlation method (in the absence of heat haze) as well as those induced by heat haze. These functions offer insight into the performance of the stereo-DIC system in the presence of heat haze, considering the specific thermal

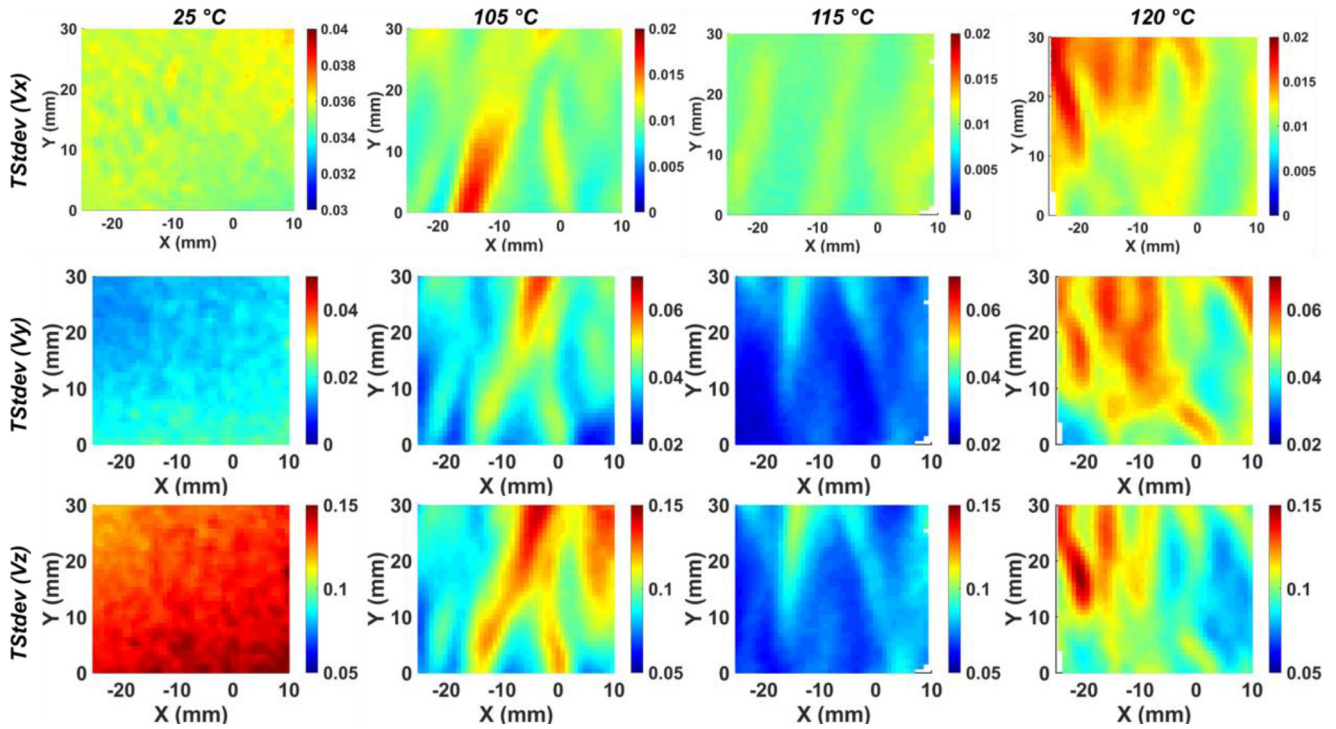


Fig. 10. Full fields of temporal standard deviations (TStddev maps) evaluated from tests conducted at 50 mm/min at a time stamp of 9 s.

equipment and protocol employed to generate heat haze. In more practical terms, several challenges must be overcome before applying this approach more broadly. First, in the case of laboratory-scale tests with short characterization durations (e.g., tensile tests, bulging tests), extensive campaigns remain needed with and without heat haze. Collected data can be used to construct an empirical dataset, and extrapolation techniques can be applied to characterize the performance of the “thermal/optical” system. However, the authors clarify that suggesting an extrapolation approach falls beyond the current study’s scope. Second, in the case of laboratory-scale tests with extended characterization durations (e.g., creep tests), the current solution may be impractical due to the extensive nature of data collection required by stereo-DIC and the spatial-temporal scales of optical distortions caused by heat haze. Third, in the case of in-situ stretching or open-mould thermoforming equipment instrumentation, further improvements are needed. Importantly, the time evolution of bias errors under the combined effects of speed and temperature in the presence of heat haze should be considered. Therefore, the temporal evolution of corrective functions serves as an initial step towards a better understanding of the heat haze effect when conventional filtering solutions are not applicable.

4 Conclusions

The primary conclusions drawn from this study pertain to the evaluation of systematic errors and noise based on rigid body tests conducted across the range of thermoforming

temperatures. A distinctive aspect of the study lies in (i) the recreation of heat haze using a partially-open vertical enclosure, and (ii) the application of a laboratory-scale stereo-DIC system in a specific context imitating industrial scenarios where conventional filtering methods, such as applying forced air flows, are not easily applicable. Firstly, the experimental verifications underscored the necessity to scrutinize the heating chamber’s performance and objectively establish the reference state of displacements, as monitoring the speckle during temperature regulation is challenging, akin to the thermoforming process. Secondly, the assessment of temporal random errors revealed the sensitivity of noise to illumination quality, as evident at 25 °C and by varying displacement speeds. However, primary attention was directed towards the impact of heat haze, assuming negligible blackbody radiation. In the presence of heat haze, noise distributions indicated localized fluctuations that intensified as the regulated temperature increased. These fluctuations were corroborated by measured angular deviations of the speckle surface and the presence of localized feather-shaped heat plumes. Thirdly, the time evolution of systematic errors at 25 °C revealed a dependence on the imposed displacement speed. However, within the considered temperature range, systematic errors decreased, evident from changes in the bias error profile slopes. Nevertheless, an unusual alteration of bias errors at a speed of 100 mm/min was hypothetically linked to the potential influence of turbulent convective effects of hot air, alongside natural convection, as predicted by thermal turbulence considerations. By assuming the additive decomposition of systematic errors

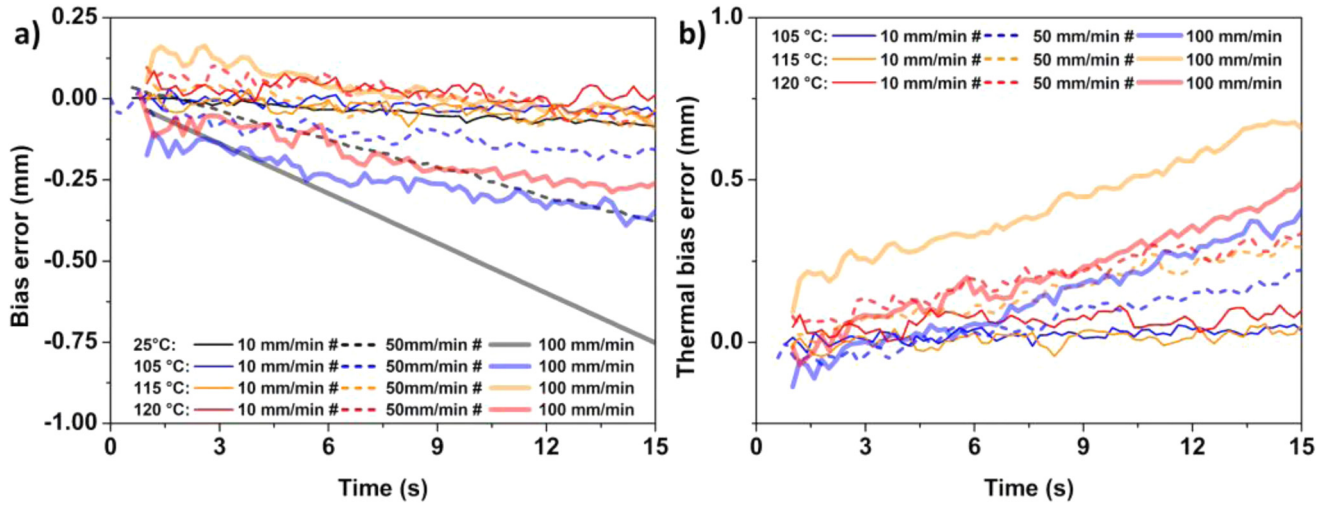


Fig. 11. (a) Time evolution of global systematic errors. (b) Time evolution of thermal bias errors.

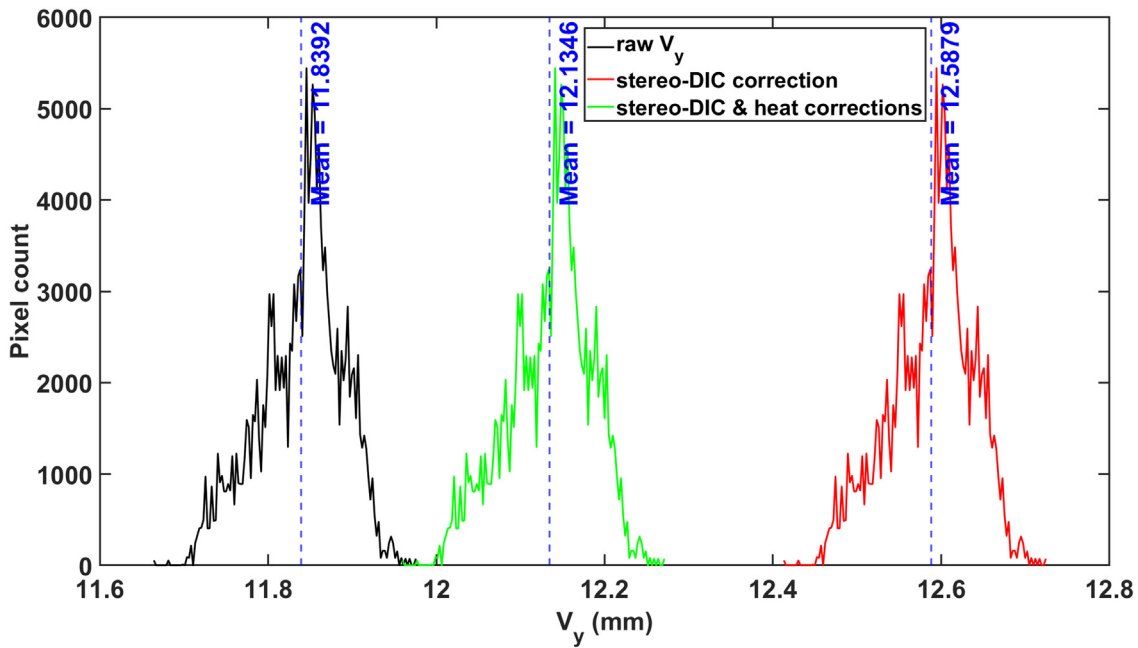


Fig. 12. Histogram distributions illustrating the effect of filtering global systematic errors and thermal haze induced systematic errors.

into errors induced by stereo-DIC measurements in the absence of heat sources and errors stemming from heat haze, a temporal correction scheme was proposed. These functions encapsulate the temporal evolution of bias errors and characterize the calibrated system's "lack of performance" in the presence of heat haze, accounting for specific thermal and optical challenges. Considering the case of application, this correction procedure demonstrated an approximate 44% enhancement in the precision of measured displacements.

In addition to these findings, the suggested correction scheme can be applied to rectify macroscopic spatial displacements based on statistical descriptors over the

designated region of interest, and local time correction within the center of subsets based on temporal standard deviation maps. Despite the feasibility of the proposed filtering approach, a few limitations remain unresolved within this study's scope, notably (i) the need for extensive replications of stereo-DIC measurements both with and without heat haze, and (ii) the adaptability of the approach primarily to short-time tests. Further research is needed to (i) gain deeper insights into convective heat turbulence at displacement speeds exceeding 100 mm/min, and (ii) extend the correction procedure to high-temperature stretching tests of thermoformable polymers.

Appendix A

This appendix provides supplementary data conducted on a second specimen in the case of a “non-moving specimen”. The corresponding data are also used for supporting information related to the characterizations of the speckle in [Section 2.1](#) of the main manuscript.

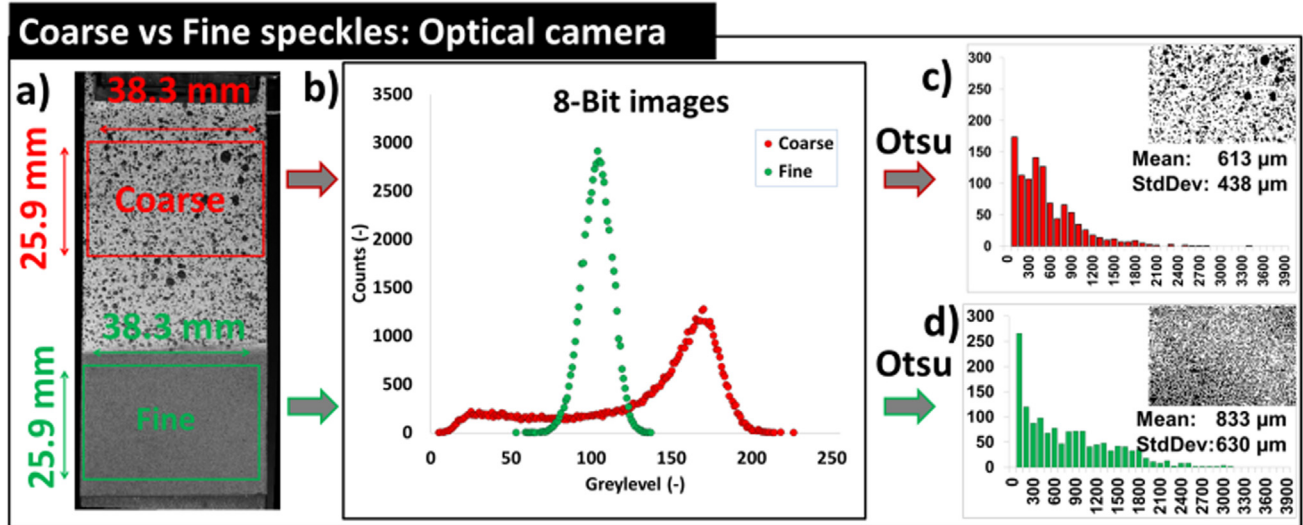


Fig. A1. Exploring two speckled zones of the same specimen: unveiling insights from (a) optical image captured by the left camera of the stereo-DIC system, (b) corresponding greylevel histograms for low density (denoted by coarse) and high density (denoted by fine) of black patterns, and (c) Size distributions of dark patterns post an automatic greylevel thresholding using an Otsu filter.

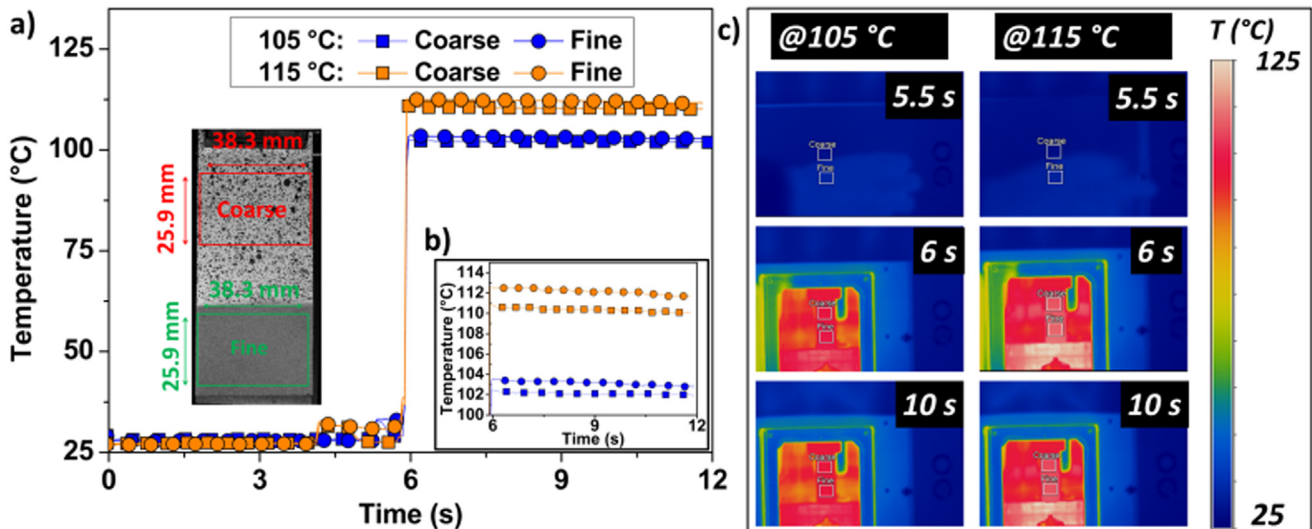


Fig. A2. (a) Temporal evolution profiles of average temperatures in the coarse and fine speckled regions, assuming emissivity as unity (equal to 1), (b) Zoomed view highlighting temperature discrepancies due to variations in speckle density in Coarse and Fine zones and (c) Representative thermograms captured by the IR camera, illustrating the measurement zones for two tests conducted respectively at 105 $^{\circ}\text{C}$ and 115 $^{\circ}\text{C}$.

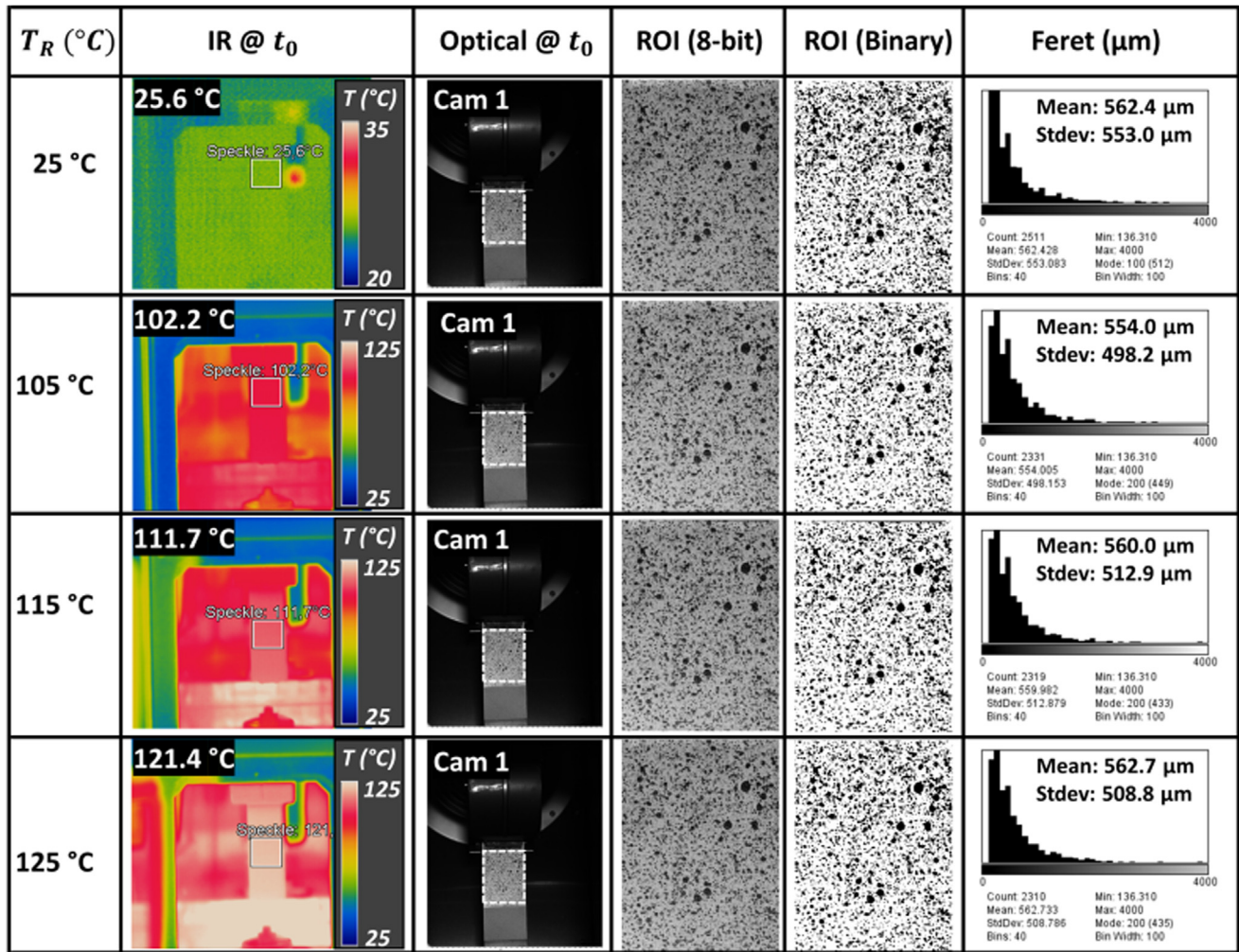


Fig. A3. Complementary experimental verification of potential thermal degradation of the applied paint speckle. All results correspond to the same speckle patterns used in the case of a “non-moving” specimen.

Appendix B

Table B1. Physical properties of air at an absolute temperature of 310 K (values from [35]).

g	Gravity (m/s^2)	9.81
β	Thermal expansion coefficient ($1/\text{K}$)	3.37×10^{-3}
ν	Kinematic viscosity (m^2/s)	1.53×10^{-5}
α	Thermal diffusivity (m^2/s)	2.15×10^{-5}

Appendix C

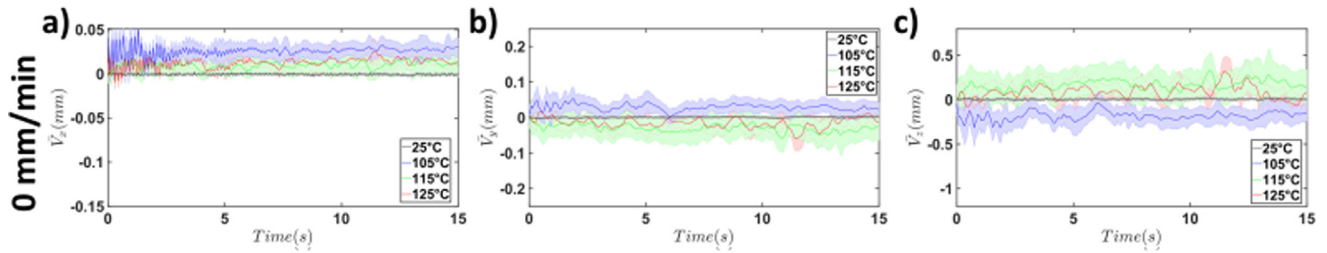


Fig. C1. Time evolution baselines of means (continuous lines) and standard deviations (background bands) calculated from displacement components: (a) $\bar{V}_x$, (b) $\bar{V}_y$ and (c) $\bar{V}_z$ obtained from “non-moving” specimen tests (i.e., at a speed of 0 mm/min). The average displacement components are quantified in millimeters.

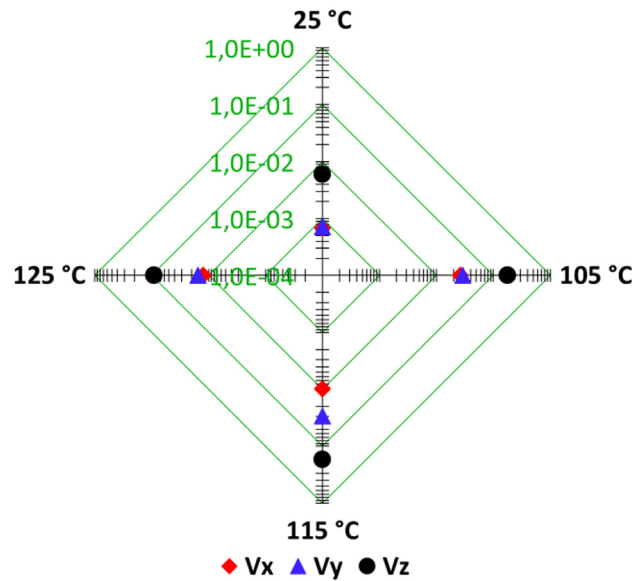


Fig. C2. Graph depicting the absolute values of the average measured displacement components from the “non-moving” specimen. Measurements are in millimeters, and the axis graduation employs a logarithmic scale.

Table C1. Intrinsic and extrinsic parameters obtained from calibration of the stereo-DIC system.

Parameters	1 st calibration		2 nd calibration	
	Cam. 1	Cam. 2	Cam. 1	Cam. 2
Rotations (°)	37.034, -2.979, -2.157	36.014, 6.378, -0.854	15.849, -3.374, -0.012	17.421, 7.240, -0.777
Positions (mm)	-14.246, -195.191, 645.764	-22.327, -192.428, 653.943	-17.615, -90.698, 711.903	10.051, -112.259, 857.874
Focal length (mm)	43.158	43.340	41.422	49.152
Scale factor (pixel/mm)		11.151		10.496

Appendix D

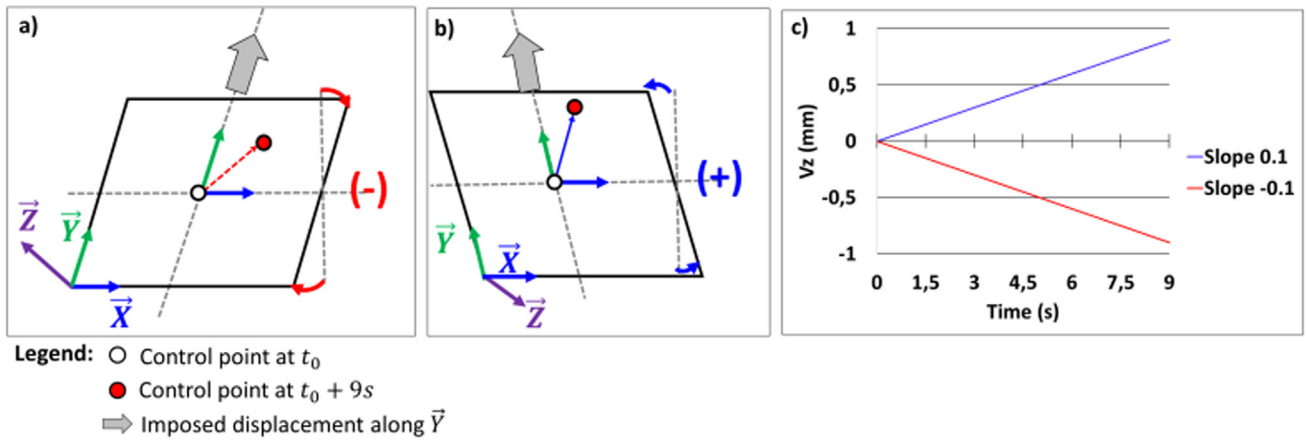


Fig. D1. (a) Illustrative representation of first scenario, (b) illustrative representation of second scenario, (c) the corresponding temporal evolution of displacement component V_z following during displacement imposed along $\vec{Y}$ direction for 9 s.

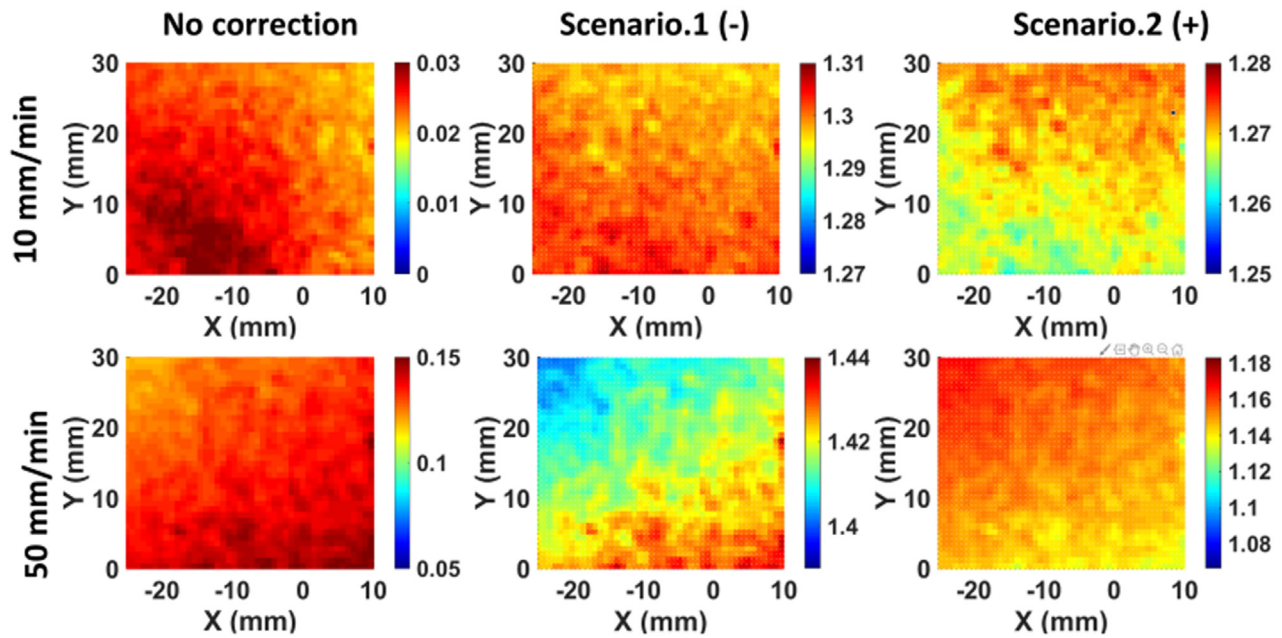


Fig. D2. Full fields of temporal standard deviations as provided in Figure 9 and Figure 10 with no modification. And corresponding changes according to the suggested scenarios 1 & 2.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability statement

The datasets for this manuscript are the property of IMT Nord Europe and are not publicly available. Requests to access the primary data should be addressed to the corresponding author.

Funding

In relationship to the 2022 CFM conference, the authors thank the French Association of Mechanics (AFM) for covering the article processing charges.

The authors acknowledge the European Regional Development Fund FEDER, the French state and the Hauts-de-France Region council for co-funding the PhD grant of Mr. A.G. Dastidar.

Author contributions

A.G.D contributed to the experimental work, data post-processing and to the interpretation of results. A.A. contributed to experiment design, data-post processing, interpretation of results and was in charge of drafting the article. M-F Lacrampe. was in charge of the global project management and draft checking.

References

- [1] Y. Wang, P. Lava, S. Coppieters, P. V. Houtte, D. Debruyne, Application of a multi-camera stereo DIC set-up to assess strain fields in an Erichsen test: methodology and validation, *Strain*. **49**, 190–198 (2013)
- [2] P. Duchene, S. Chaki, A. Ayadi, P. Krawczak, A review of non-destructive techniques used for mechanical damage assessment in polymer composites, *J. Mater. Sci.* **53**, 7915–7938 (2018)
- [3] A. Ayadi, M-F. Lacrampe, P. Krawczak, A comprehensive study of bubble inflation in vacuum-assisted thermoforming based on whole-field strain measurements, in: AIP Conf. Proc., 2018, p. 120004.
- [4] A. Ayadi, M-F. Lacrampe, P. Krawczak, Assessment of the elongational properties of HIPS membranes based on full-field strain measurements during positive thermoforming, 12th International Conference on Advances in Experimental mechanics, August 2017, Sheffield, United Kingdom. <https://imt.hal.science/view/index/identifiant/hal/-01779760>
- [5] Ghosh Dastidar, A. Ayadi, M-F. Lacrampe, Reliability of hybrid inverse identification based on stereo-dic measurements to assess HIPS hyperelastic parameters: case of isothermal tensile loads, *Procedia Manuf.* **47**, 933–939 (2020)
- [6] J.A. Turner, G.H. Menary, P.J. Martin, Biaxial characterization of poly(ether-ether-ketone) for thermoforming: a comparison between bulge and in-plane biaxial testing, *Polym. Eng. Sci.* **59**, 1853–1865 (2019)
- [7] B. Van Mieghem, J. Ivens, A. Van Bael, Consistency of strain fields and thickness distributions in thermoforming experiments through stereo DIC, *Exp. Tech.* **40**, 1409–1420 (2016)
- [8] B. Van Mieghem, F. Desplentere, A. Van Bael, J. Ivens, Improvements in thermoforming simulation by use of 3D digital image correlation, *Express Polym. Lett.* **9**, 119–128 (2015)
- [9] M. Neubauer, M. Dannemann, N. Herzer, B. Schwarz, N. Modler, Analysis of a film forming process through coupled image correlation and infrared thermography, *Polymers (Basel)*. **14**, 1231 (2022)
- [10] R. Bigger, B. Blaysat, C. Boo, M. Grewer, J. Hu, A. Jones, M. Klein, K. Raghavan, P. Reu, T. Schmidt, T. Siebert, M. Simenson, D. Turner, A. Vieira, T. Weikert, A good practices guide for digital image correlation, *Int. Digit. Image Correl. Soc.*(2018). DOI:10.32720/IDICS/GPGED1.
- [11] M.A. Sutton, F. Hild, Recent advances and perspectives in digital image correlation, *Exp. Mech.* **55**, 1–8 (2015)
- [12] B. Beaubier, J.-E. Dufour, F. Hild, S. Roux, S. Lavernhe, K. Lavernhe-Taillard, CAD-based calibration and shape measurement with stereoDIC, *Exp. Mech.* **54**, 329–341 (2014)
- [13] T. Siebert, E. Hack, G. Lampeas, E.A. Patterson, K. Splittthof, Uncertainty quantification for DIC displacement measurements in industrial environments, *Exp. Tech.* **45**, 685–694 (2021)
- [14] Y. Sieffert, F. Vieux-Champagne, S. Grange, P. Garnier, J. C. Duccini, L. Daudeville, Full-field measurement with a digital image correlation analysis of a shake table test on a timber-framed structure filled with stones and earth, *Eng. Struct.* **123**, 451–472 (2016)
- [15] X. Shao, X. He, Camera motion-induced systematic errors in stereo-DIC and speckle-based compensation method, *Opt. Lasers Eng.* **149**, 106809 (2022)
- [16] S. Barone, P. Neri, A. Paoli, A.V. Rationale, Low-frame-rate single camera system for 3D full-field high-frequency vibration measurements, *Mech. Syst. Signal Process.* **123**, 143–152 (2019)
- [17] R. Balcaen, P.L. Reu, P. Lava, D. Debruyne, Influence of camera rotation on stereo-DIC and compensation methods, *Exp. Mech.* **58**, 1101–1114 (2018)
- [18] Y. Su, Z. Gao, Q. Zhang, S. Wu, Spatial uncertainty of measurement errors in digital image correlation, *Opt. Lasers Eng.* **110**, 113–121 (2018)
- [19] R. Balcaen, P.L. Reu, P. Lava, D. Debruyne, Stereo-DIC uncertainty quantification based on simulated images, *Exp. Mech.* **57**, 939–951 (2017)
- [20] E.M.C. Jones, P.L. Reu, Distortion of digital image correlation (DIC) displacements and strains from heat waves, *Exp. Mech.* **58**, 1133–1156 (2018)
- [21] M. Berny, T. Archer, A. Mavel, P. Beauchêne, S. Roux, F. Hild, On the analysis of heat haze effects with spacetime DIC, *Opt. Lasers Eng.* **111**, 135–153 (2018)
- [22] J.S. Lyons, J. Liu, M.A. Sutton, High-temperature deformation measurements using digital-image correlation, *Exp. Mech.* **36**, 64–70 (1996)

- [23] L. Yu, B. Pan, Overview of high-temperature deformation measurement using digital image correlation, *Exp. Mech.* **61**, 1121–1142 (2021)
- [24] A. Yuile, R. Schwerz, M. Roellig, R. Metasch, S. Wiese, Heat haze effects in thermal chamber tensile tests on digital image correlation, in: 2018 19th Int. Conf. Therm. Mech. Multi-Physics Simul. Exp. Microelectron. Microsystems, IEEE, 2018, pp. 1–7. 8369882.
- [25] C. Ma, Z. Zeng, H. Zhang, X. Rui, A correction method for heat wave distortion in digital image correlation measurements based on background-oriented schlieren, *Appl. Sci.* **9**, 3851 (2019)
- [26] A. Ghosh Dastidar, A. Ayadi, M-F. Lacrampe, Reliability of hybrid inverse identification based on stereo-DIC measurements to assess HIPS hyperelastic parameters: case of isothermal tensile loads, *Procedia Manuf.* **47**, 933–939 (2020)
- [27] B. Van Mieghem, J. Ivens, A. Van Bael, Consistency of strain fields and thickness distributions in thermoforming experiments through stereo DIC, *Exp. Tech.* **40**, 1409–1420 (2016)
- [28] A. Ghosh Dastidar, Modeling and Simulation of Thermoforming, doctoral thesis, IMT Nord Europe, 2022
- [29] A. Ayadi, M-F. Lacrampe, P. Krawczak, Bubble assisted vacuum thermoforming: considerations to extend the use of in-situ stereo-DIC measurements to stretching of sagged thermoplastic sheets, *Int. J. Mater. Form.* **13**, 59–76 (2020)
- [30] E. Bilgen, H. Oztup, Natural convection heat transfer in partially open inclined square cavities, *Int. J. Heat Mass Transf.* **48**, 1470–1479 (2005)
- [31] A. Ayadi, H. Nouri, S. Guessasma, F. Roger, Large-scale x-ray microtomography analysis of fiber orientation in weld line of short glass fiber reinforced thermoplastic and related elasticity behavior, *Macromol. Mater. Eng.* **301**, 907–921 (2016)
- [32] I.V. Miroshnichenko, M.A. Sheremet, Turbulent natural convection heat transfer in rectangular enclosures using experimental and numerical approaches: a review, *Renew. Sustain. Energy Rev.* **82**, 40–59 (2018)
- [33] B. Zhao, Derivation of unifying formulae for convective heat transfer in compressible flow fields, *Sci. Rep.* **11**, 16762 (2021)
- [34] R. Harish, Buoyancy driven turbulent plume induced by protruding heat source in vented enclosure, *Int. J. Mech. Sci.* **148**, 209–222 (2018)
- [35] A. Saxena, V. Kishor, S. Singh, A. Srivastava, Experimental and numerical study on the onset of natural convection in a cavity open at the top, *Phys. Fluids.* **30**, 057102 (2018)
- [36] S.B. Dalziel, G.O. Hughes, B.R. Sutherland, Whole-field density measurements by “synthetic schlieren,” *Exp. Fluids.* **28**, 322–335 (2000)
- [37] H. Richard, M. Raffel, Principle and applications of the background oriented schlieren (BOS) method, *Meas. Sci. Technol.* **12**, 1576–1585 (2001)
- [38] P.E. Ciddor, Refractive index of air: new equations for the visible and near infrared, *Appl. Opt.* **35**, 1566 (1996)
- [39] L. Yu, B. Pan, The errors in digital image correlation due to overmatched shape functions, *Meas. Sci. Technol.* **26**, 045202 (2015)

Cite this article as: A.G. Dastidar, A. Ayadi, M-F. Lacrampe, Experimental quantification of heat haze errors in stereo-DIC displacements: Application to thermoplastics thermoforming temperature range, **24**, 39 (2023)