U.P.B. Sci. Bull., Series D, Vol. 85, Iss.1, 2023 ISSN 1454-2358

THERMAL CALIBRATION OF AN AXISYMMETRIC HEATED AIR JET BY MEANS OF QUANTITATIVE SCHLIEREN

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The configuration of a calibrated schlieren system varies with the type of the flow to be analyzed. This paper presents an experimental study on the topic of temperature determination of an axisymmetric turbulent heated flow, through post-processing, while keeping the focus on the jet area rather than on the optical correlation between the jet and the calibrating element. The temperature profile is correlated to the contrast and sensitivity of the system. Different aspects of the calibration problem are discussed; the proof of concept and the calibration curves are achieved and discussed.

Keywords: experimental, calibrated schlieren, air jet, thermal calibration

1. Introduction

Schlieren systems are optical systems used to capture density gradients in transparent media. The first calibrated system configuration is attributed to Schardin. This setup uses a large focal-length lens with a small diameter as a calibration element, which is introduced in an undisturbed area of the parabolic mirror's field of view which helps determining the displacement of the collimated light ray [1].

The simplest configuration of a schlieren system uses a single parabolic mirror, setup which is known as the *Toepler* configuration [2] (named after Auguste Toepler). By using a single parabolic mirror, the system becomes easier to align, maintains its large field of view, while taking up not as much space as the Z-type configuration which incorporates two parabolic mirrors placed at a considerable distance between them, while keeping in mind that other optics placed in front of the light source or in front of the camera, need to have an offset angle relative to each mirror's axis [3].

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The deflection angle can be determined by post-processing the images of the studied phenomena and density gradients can be extracted from the distribution of the refractive index.

A very important study on the matter of calibrating schlieren systems has been conducted by Elsinga et. al [4], and it concerns the matter of comparing two different quantitative methods: the color calibrated filter schlieren method and the background oriented schlieren method, known as BOS.

The application chosen created a certain disadvantage for the BOS technique, the aim being the investigation of density gradients which are created inside a supersonic wind tunnel. The second paper worth mentioning is the comparison of three different calibrated schlieren methods [5], which adds to the first one a “new non-traditional BOS method”, based on the digitalisation of the system, resulting into quantitative results obtained from the recorded pictures through post-processing.

Despite the fact that the last-mentioned study has been conducted in a more favourable context, when the digital era was much improved, it does not rely solely on the calibrated filter used, but rather prefers to take a shortcut. The shortcut mentioned represents leaving the calibration lens in place for the rainbow setup as well, allowing a faster calibration of the step-color varying filter. Elsinga et. al accomplish the color filter calibration on its own, and underlying the possibility to replace the calibration lens with computing power.

Many commercial schlieren systems are available on the market, but unfortunately, none so flexible to cover the entire experimental spectrum of the flow analysis field. As far as the quantitative issue is concerned, this is covered in the first two presented studies.

Regarding the temperature measurement matter, [6] presents an interesting approach. The focusing schlieren method used here can be applied to an entire flow field rather than generating the expected path integrated results. The SFS (Sharply Focused Schlieren) uses the chromatic aberration effect to focus different wavelengths of white light on the lens’optical axis thanks to the dispersion effect. This effect focuses the frequencies close to red away from the lens, and the blue frequencies closer to it. This split can be achieved by using a digital color camera. It uses a multi-light source with multiple point-like sources, which helps determine the flow’s character in a very narrow depth of field plane. By using an off -axis not corrected for chromatic aberration schlieren lens and the RGB illumination array, measurements of 3 different planes of the narrow DOF (Depth of Field) are made possible, which make the system perfect for measurements inside non-symmetrical fluid flows [6].

This method also has its shortcomings, the source of errors and a value of the measurement uncertainty are not provided, although the comparison with the thermocouple measured values of the same flow indicates an error of about 6.5%, which is more than twice the value obtain in most studies centered around quantitative schlieren.

The issues to be addressed through this paper is the thermal calibration of an axisymmetric heated flow, necessary in a situation where the experimental setup provides optical access to the flow field, but the thermal camera cannot "see" the flow due to the jet's low emissivity which is being absorbed by the transparent windows of the setup. Such an issue has been encountered when the temperature map of a water vapour jet resulting from a $H_2 - O_2$ reaction couldn't be captured by the thermal camera.

A system relying solely on post-processing schlieren images uses no intrusive measuring equipment and more computing power, which is easier to find given the digital context of the modern era.

2. Test case description

The system calibrating the flow provides a self-calibrating procedure. In the case of a low-emission-high-temperature flow for which optical access is provided, a calculation of the said emission has to be conducted first.

The problem was firstly encountered when the jet coming from a micro-thruster couldn't be observed and quantified by using a thermal camera (Cedip Silver 420). The temperature the exiting jet has is really high, but given the fact that the resulting gas is composed out of water vapors, a calculation for the emissivity of the jet has to be conducted. The emissivity of the jet can be calculated by applying the next formula:

$$\boldsymbol{\varepsilon_{fl} = 1 - e^{-kps}} \tag{1}$$

Where the CO_2 mass fraction can be calculated here with (2), and p is, in this case, the lowest value of the pressure found in the flame (considered as such in order to achieve the lowest emissivity value that the thermal camera will have to be able to detect).

$$\mathbf{k} = \left[\frac{0{,}78 r_{CO_2} + 1{,}6 r_{H_2O}}{\sqrt{p(r_{H_2O} + r_{CO_2})s}} - \mathbf{0,1}\right]\left(\mathbf{1 - 0,37}\frac{T}{1000}\right) \tag{2}$$

Characteristics of the flow to be calculated are found in *Table1*.

Table 1

$H_2 - O_2$ jet characteristics

Parameter's name	Notation	Value	Unit of measure
Hydrogen's mass flow rate	$\dot{m}_{H_2}$	0,0345	[g/s]
Oxygen's mass flow rate	$\dot{m}_{O_2}$	0,285	[g/s]

Atmospheric temperature	T	288	[K]
Flame diameter (exiting jet)	D_{fl}	32	[mm]
Emissivity coefficient*	*s*	0.9D	[mm]
Range of camera relative to the measuring point	*D*	1	[m]
Volume fraction of water vapors	r_{H_2O}	1	-
Emissivity constant	*k*	0.19	-

From (1) and (2), with the data from *Table 1*, and taking into account that the resulting product consists out of water vapors only, the CO_2 mass fraction can be considered 0, the emissivity of the jet resulting to be:

$$\boldsymbol{\varepsilon_{fl} = 0,156} \quad (3)$$

The emissivity coefficient and the volume fraction of the water vapors are provided by specialty tables [7].

The equivalent emissivity the camera captures is corrected for the air emissivity (ε_{air}) , and it's described by:

$$\boldsymbol{\varepsilon_{ech} = \varepsilon_{fl} - \varepsilon_{air}} \quad (4)$$

The resulted emissivity is $\varepsilon_{ech} \approx 0.155$. The thermal camera cannot correct for such a low emissivity value, only increments higher than 0.2 being relevant.

The emissivity value found is in good agreement with several values found in literature [8], all depending on the quantities presented above. The calculation described above prove the need of a self-calibrated system. A jet that has a similar geometry, but works on a different temperature range, has been used to test the concept of schlieren thermal calibration.

The purpose of the paper is to calibrate a heated, axisymmetric air jet by obtaining a contrast and sensitivity curve as a function of pixel intensity.

The emissivity of the jet is not questioned in a schlieren system; schlieren is based on the density gradient observation. The density gradient becomes more observable if the flow's temperature rises or decreases, creating a higher disturbance in the field of view than the natural convection of the room which is also visible if the system is sensitive enough.

3. Optical configuration

As mentioned before, a heated axisymmetric air jet will be calibrated for different increasing temperature values in the 50°C ÷ 180°C interval, with a 10°C increment.

Even though the jet is axisymmetric and an Abel inverse integral can be used to obtain the density field distribution from path integrated data [9,10], the present application can be considered to have the same integration path when the jet reaches a temperature stability (the jet is captured at 15 seconds after starting the jet generator for every set of images).

The geometry of the jet does not vary very much with time, so an average based on 50 images per temperature series is found to be enough to correct for the geometry variation.

The experimental setup is presented in Fig. 1. The chosen setup is *Toepler*, the single parabolic mirror schlieren configuration.

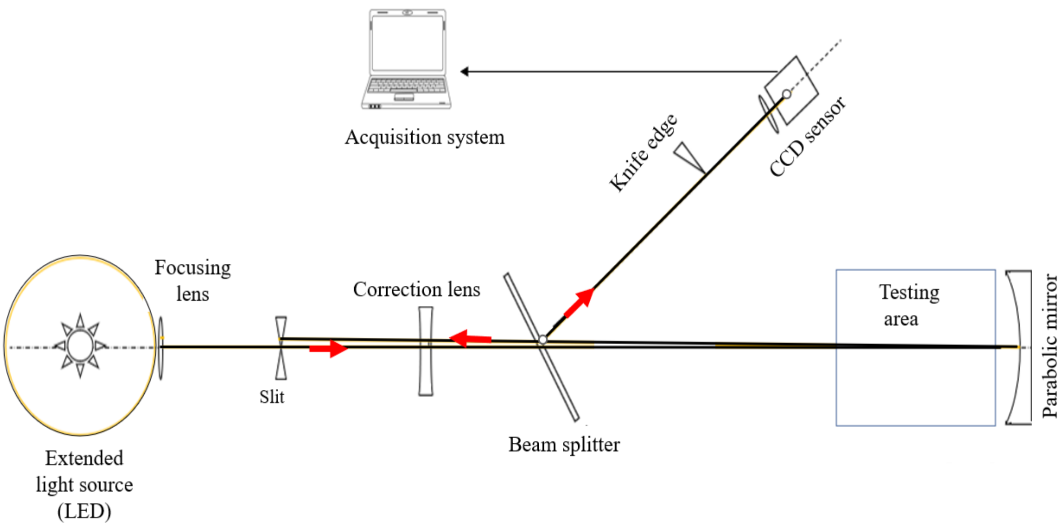


Fig. 1 Schlieren experimental configuration

Toepler's configuration has many advantages, the most important is the fact that it uses only one parabolic mirror. The parabolic mirror used in this configuration is a 10" Diameter, a 60" focal length and protected with an Aluminum coating, with a very good surface accuracy, resulting in a very precise response which eases the optical alignment. The main drawback of this configuration is the double image given by the reflected beam, returning on the same path as the incident beam and in this way double crossing the phenomena. There are more ways to correct this issue. [11] specifies that the double imaging can be avoided by minimizing the distance between the light source and the knife edge, which is not always possible to achieve. Therefore, the solution adopted for this study is placing a beam splitter to refract just one beam onto the CCD (Charged Coupled Device sensor belonging to the high-speed camera).

The optical path towards the parabolic mirror consists out of an extended light source after which one can place a focusing lens which brings the light to a focus into a single point. This point is reduced afterwards by a source slit, similar to a camera diaphragm. The light source, focusing lens and the slit forms an ideal point-like light source. The diaphragm (or source slit) reduces the source's dimeter without cutting a lot of its intensity which would happen without the use of the focusing lens. The correction lens is inserted to collimate the point-light source as much as possible and send it to the center of the parabolic mirror. The parabolic mirror's response is refracted by the beam splitter on the CCD sensor. The CCD sensor is placed at the appropriate distance behind the focused light, far enough to allow the whole mirror to appear filled by light while allowing the knife edge to be placed in the focal point.

For this type of system, the setup is important because the accuracy of the experiment depends on the accuracy of the optical alignment. The optical alignment represents the main source of errors for a visualization method converted into a quantitative method.

For a proper measurement, it has to be taken into account that, except for the BOS technique, all of the other schlieren configurations focus on the studied phenomena and not on the background (in this case, mirror). Generally, the configuration needs to be adapted to the phenomena's geometric requirements.

The system is easier to put in place if a pre-setup is established beforehand. After this, the best way to achieve a precise alignment in a short period of time is to design the adequate supports for the optical elements.

A fast and precise way to do so it is to rely on a cad design transferred directly into the 3D printer. Offset angles and inclinations can be applied directly, reducing time spent on optical alignment. 3D printing was used in the presented system to help build it around the desired testing area.

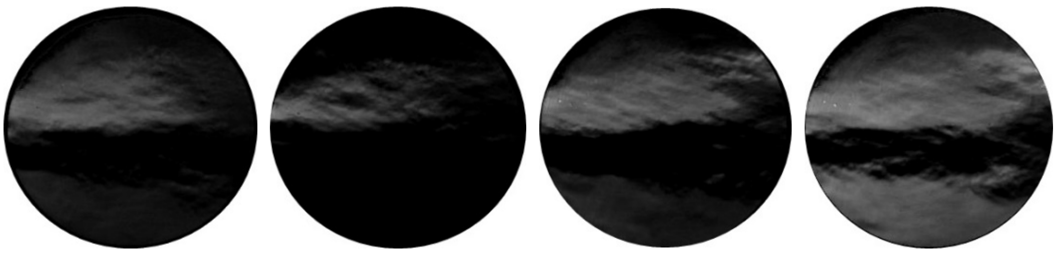
The experiment's goal is to obtain a calibration curve for the jet, and see if such a curve can be achieved for any type of jet, if the proper corrections for its nature are applied.

4. Experiment unfolding

The experiment begins by fixing a thermostat near the schlieren system in order to keep track of the rising room temperature. No other temperature is allowed to disturb the schlieren imaging session (for example: no air conditioning on, no radiator and no sunlight are allowed inside the testing area). It is easier to correct for the rising temperature by firstly capturing a series of background images and then write an averaged image which is to be extracted from the temperature measuring images that contain the heated jet. In this way, one corrects also for the natural convection in the room (air currents, thermal plumes caused by human body presence, etc.). To have a more accurate result, background images must be taken before all temperature series and preferably at a 15 minutes window between series, allowing the installation to cool down and the air currents to settle. High variation of the testing room's temperature has been observed to be quite high; the temperature varies linearly with the rise of the temperature jet, but it is canceled through background subtraction and natural convection averaging.

5. Results and discussion

When visually analyzing the jet images after the background subtraction is performed, one might think that the overall intensity of the image increases, but that becomes clearly false at higher jet temperature, where the image's details start to darken as well as brighten on some of the areas.



a) b) c) d)

Fig. 2 Images of the heated air jet with background subtraction at: a) 50°C, b) 60°C, c) 70°C and d) 80°C

One can thus, speculate that the one changing is actually the image contrast. Settles [12] defines contrast as the ratio between local illuminance and general illuminance.

$$\mathbf{C} \equiv \frac{\Delta \mathbf{E}}{\mathbf{E}} \tag{5}$$

Others use a variation of this formula [13] in which the contrast can also be written as a ratio between the increment gain of illumination times the area of light that has not been cut-off by the knife edge and the magnification factor multiplied by the square of the first focal distance.

The sensitivity of the system plays an important role as well. General sensitivity increases with the percent of the cut off of the knife edge. In this case, it will be quantified as it was by Settles [3], as the ratio of local contrast and the refraction angle:

$$\mathbf{S} = \frac{\Delta \mathbf{C}}{\mathbf{d}\boldsymbol{\varepsilon}} \tag{6}$$

The refraction angle's value used in calculation is considered the general averaged value. As mentioned before, several background images have been taken for each temperature series to be recorded. An average per pixel was performed for a 50 images batch and an average-intensity background image was written, becoming the subtracted background image. After this, the heated jet was recorded into multiple frames. An average image of the jet has been obtained in a similar manner to the background, and this became the image to be analyzed and compared.

Usually, this type of analysis is performed locally (per pixel), but the paper itself concentrates on a more general description, so an average intensity per column is performed in the average image's matrix, and for that value, contrast and sensitivity calculations are performed.

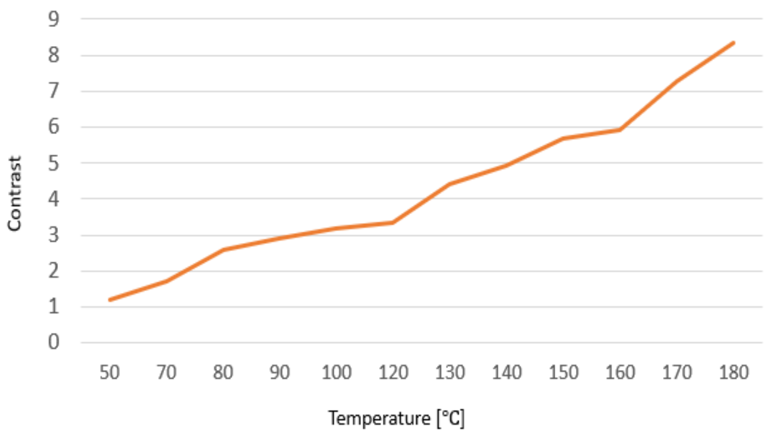


Fig. 3 Contrast variation with jet temperature

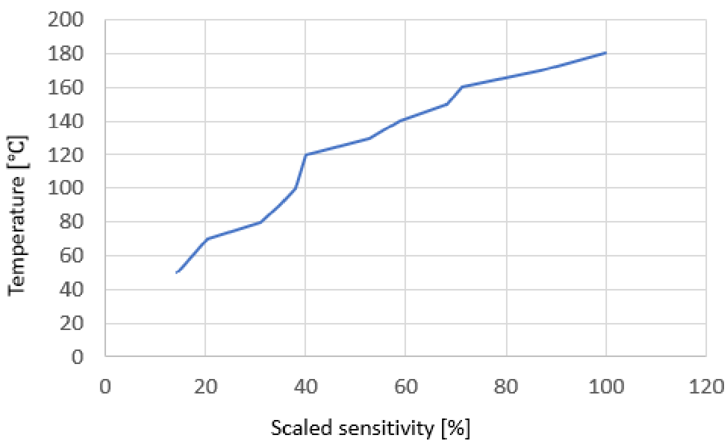


Fig. 4 Scaled sensitivity of the images

A rise in contrast can be observed with the increasing temperature. This curve can be considered to be fitting as a calibration curve, because the sensitivity calculated per temperature series uses an averaged reflection angle (*Table 2*), which is considered to be constant for all sensitivity points.

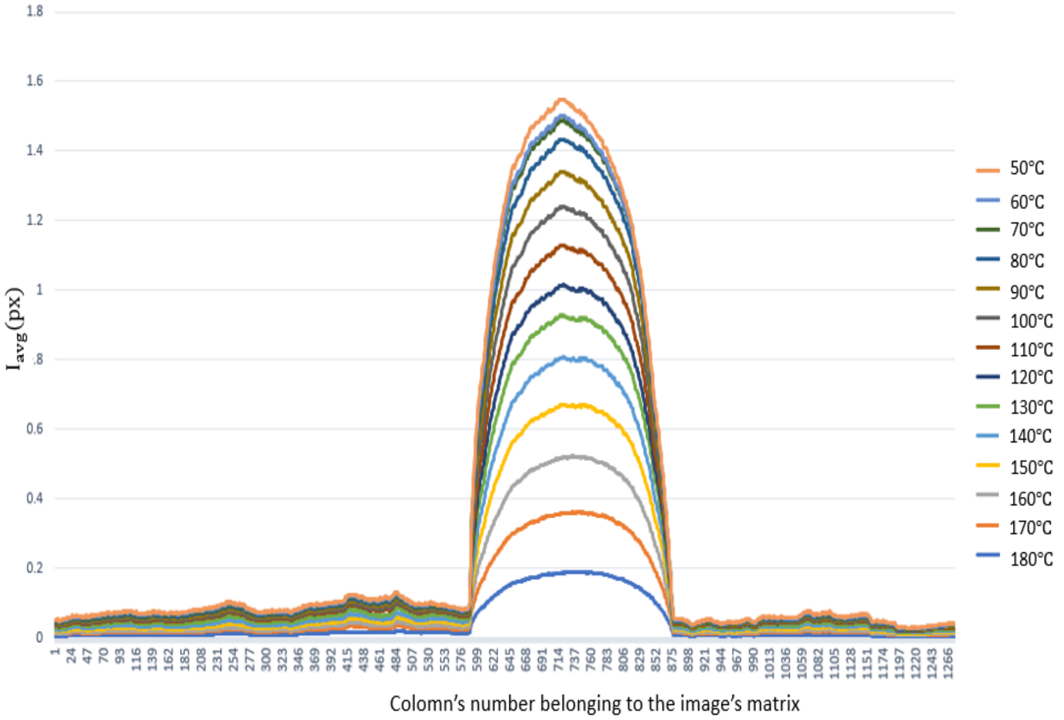


Fig. 5 Averaged pixel intensity values per column for each temperature series

The average of pixel intensity performed by column for each averaged image of every temperature series, will show a clear framing of an unknown temperature value, analyzed in a limited spectrum of intensity, fact that can be observed in Fig.5.

Table 2

Quantifiable parameters obtained from temperature series images

T [°C]	ΔE	Contrast	T_{room} [°C]	E average/image	Ref angle (mrad)	Raw sensitivity	S %
50	0.009484881	1.185610129	27	0.008	0.00278	426.4784635	14.21595
70	0.012138989	1.704196104	27	0.007123	0.00278	613.0201814	20.43401
80	0.019231949	2.579392335	27	0.007456	0.00278	927.8389695	30.92797
90	0.020401522	2.921877475	27	0.006982333	0.00278	1051.035063	35.0345
100	0.021310938	3.17583897	28	0.006710333	0.00278	1142.388119	38.0796
120	0.021550596	3.347232088	28	0.006438333	0.00278	1204.040319	40.13468

130	0.027151672	4.40321192	28	0.006166333	0.00278	1583.88918	52.79631
140	0.028985302	4.917486027	28.5	0.005894333	0.00278	1768.879866	58.96266
150	0.032013629	5.694011272	28.5	0.005622333	0.00278	2048.205493	68.27352
160	0.031743414	5.932978769	28.5	0.005350333	0.00278	2134.165025	71.13883
170	0.036816463	7.249713731	28.5	0.005078333	0.00278	2607.810695	86.92702
180	0.039994867	8.32128456	29	0.004806333	0.00278	2993.267827	99.77559

As it can be observed, the matrix of each image also suffered a normalization. A gray filter was applied because values from 0 to 1 are easier to interpret than values from 0 to 255, for example (which are present if an 8-bit camera is used). The normalization removes the issue a color camera introduces when it is used (each pixel is being described by 3 values for each – RGB), and allows each pixel to have a single intensity value.

The sensitivity appears to be rising with the temperature. Its variation is less accurate and hence, less appropriate to be considered a calibration curve because of the refracted angle which was here considered to be the same in every point, the only variable being the contrast's value.

6. Conclusions

This paper shows that a thermal calibration of an axisymmetric jet is possible by interpreting the pixel intensity matrix, while plotting the average values from the matrix's columns.

The calculated raw sensitivity places the schlieren system used in the range of medium performance schlieren systems, but the high-density variation of the thermal calibrated flow is perfectly described within the system's performances, which images the calibrated jet without reaching its optical saturation levels.

This study can be considered proof of concept for thermal calibration of an axisymmetric jet, which will be refined in future experimental work and used to solve the initially described test case problem of the water vapor jet, by framing its temperature into a graph similar to the one described above.

The technique will help determine the temperature scale with a finer temperature grid (it can be calibrated on a more exact interval – for example, the increment can be reduced to $0.1°C$, which implies an expansion of the experimental range, arising the need for much more temperature series to be recorded, and the proper update of the schlieren system with extra optical elements in order to increase its sensitivity).

The schlieren system's response can be used to obtain a calibrating curve for a similar jet to the one which needs to be measured. A similar jet refers to a jet with similar geometry, temperature, and which creates an equal amount of density gradients. This will allow a pre-calibration of the system itself for a specific type of flow, converting the study from a jet calibrated relative to itself, to a calibration of the system.

The sensitivity parameter depends not only on the jet properties, but also very much on the system's performance and on the calibration knife edge positioning.

The main type of errors in thermal calibration are the ones belonging to the experimentation process. If the schlieren images are not captured in the same testing room illumination conditions, the knife edge is not in the same position for all temperatures considered, the room temperature variation is not accounted for, the heated jet generator's position is modified between measurements, etc. Fortunately, in this type of calibration, the jet is calibrated in relation to its own output. This fact, accompanied by a good post-processing algorithm result in a study with little to no data error.

The purpose of the experiment was to obtain a calibration curve for a heated jet for which temperature determination will be impossible to achieve through conventional methods.

The calibration curve has been obtained, and unknown temperatures of the calibrated jet can easily be determined from it.

Acknowledgement

The concept of jet calibration presented herein was first presented during the 39th "Caius Iacob" Conference on Fluid Mechanics and its Technical Applications, within a presentation, on the subject of work prospects.

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