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Study of temperature distribution over a Stirling engine by using the Schlieren technique

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ABSTRACT
The Schlieren technique has been used to visualize and measure some relevant physical properties in transparent media such as refractive index and some dependent variables on it such as density and temperature. This technique was implemented to visualize temperature gradients that appear from the heat applied into the hot section of a Stirling engine. Temperature gradients and temperature fields are described qualitatively and compared with temperature measurements using chromatic thermometric crayons. Furthermore, natural and turbulent heat convection was visualized from the temperature fields. The obtained results give important information about the heat transfer mechanism and its dissipation on a real engine.

Keywords: Schlieren devices. Image forming. Image processing. Temperature gradients. Temperature fields.

1. INTRODUCTION

The measurement of physical variables in the fluid flows area requires no intrusive techniques and instruments that no alters the dynamics of the fluid flows. As is well known the optical visualization techniques have high sensibility to measure these variables and do not perturb the media under study. For this reason in this research was used the Schlieren optical technique. The optical Schlieren technique is widely used in wind tunnels to visualize the fluid flows in aerodynamics devices such as airfoils, cylinders and blades just to mention some of the most usual applications. There is a wide variety of Schlieren arrangements used each one of them for different purposes. These arrangements changes in form and optical components like lenses, mirrors and grids, depending on the size of the field to resolve. Different light sources are used depending on the specific arrangement, like filaments, mercury, sodium, LEDs lamps, and laser sources. The Schlieren technique captures the changes of the refractive index of transparent media, which are linearly related with the gradient density and this last in its turn with the temperature gradient. The common Schlieren arrangements use now the setup originally introduced by Toepler, which includes two lenses a source light and a knife edge. In this research a modified Toepler's arrangement, common called the Z-type setup was used. This arrangement has a light source, a spherical mirror to collimate the light beam and a second mirror to concentrate the light beam in the focal plane of the setup. The knife edge is located at the focal plane of the setup and gives the refractive gradient in the image plane. The Z-type arrangement is used to increase the size of the field to visualize.

The fluid flow to visualize need to be transparent media as a principal characteristic to use this technique or in other words the fluid must to be an isotropic homogeneous media. The transparent media or phase object appears in different forms in science and engineering such compressible flows, convective heat transfer, mixing of two or more different fluid densities, combustion, plasma flow and stratified flow, [1]. This paper focuses on the hot gases produced by a flame of the mixture of

butane and atmospheric air to visualize gradient temperatures at full field from density gradients from refractive index of the hot gases with the relation of Gladstone-Dale and the ideal gas equation.

In addition, chromatic thermometer crayons were used to measure temperatures of operation in the hot surfaces changing the color surface of the crayon depending of the temperature measured.

The test object used in this work was the cylindrical hot surface of a Stirling engine heated by a mixture of butane-air. The Stirling engine invented in 1816 by Robert Stirling was used to pump water. This engine used air as work substance and was more safety than the steam engine [3]. But with the invention of Diesel and Otto cycles the Stirling engine decayed in use. In present days with the increment of renewable energies in thermo-solar and biomass systems, the use of this old technology as Stirling engines is suitable for these purposes, this justify the importance to study this technology.

2. THEORETHICAL BAKGROWND

2.1 Optical background

This chapter describes the procedure to measure temperature in fluid flows using the Schlieren technique, figure 1 shows the Z-type arrangement used in this research. When a phase object with refractive index $n = n(x, y, z)$, is located between the two mirrors, occurs a small displacement δx in the direction of propagation of the incident rays in the image plane as shown in figure 2 (the image formed in the camera). This variation in the deviation rays is linearly proportional to the changes of the refractive index. In the case of fluid flows this variation is related to the density changes as explained before. When a light ray passes through an isotropic and inhomogeneous medium this suffers a small angle deviation which depends on the refractive index and the width of the test object. The ray path is described by the ray equation shown next:

$$d(n\mathbf{P}')/ds = \Delta n \tag{1}$$

Where $\mathbf{P} = \mathbf{P}(x, y, z)$ is a position vector, $\mathbf{P}'$ is the derivative of $\mathbf{P}$ with respect to ds and $ds = dx^2 + dy^2 + dz^2$ represents the arc length along the ray propagation as shown in figure 2. The ray propagation direction is in *z*-direction, then the ray suffers small deviation in *x* and *y* directions. For simplicity here is considered the approximation in *x*-direction only, which is valid for small deviation angles given by:

$$\frac{\partial}{\partial z}\left(n\frac{dx}{dz}\right) = \frac{\partial n}{\partial x}, \tag{2}$$

The deviation angle is represented with ε, an the measured deviation in the image plane of the setup is represented with $\delta x = f_2 \tan\varepsilon \approx f_2\varepsilon$ where f_2 is the focal length of the second mirror included in the setup. In this approach the gradient of the deviation angle can be represented as:

$$\varepsilon_x = \int_{\zeta_1}^{\zeta_2} \frac{\partial n}{\partial x} dz \tag{3}$$

This equation depends on the refractive index gradient and the width of the test object defines the integration limits in z-direction ζ_2- ζ_1, as shown in figure 2. Using the Gladstone-Dale relation $(n-1) = \mathrm{K}\rho$ given by Merzkirch [1] and Settles[2], where K is the Gladstone-Dale constant, the density fluid ρ can be expressed as follows:

$$\rho_x = \frac{\partial \rho}{\partial x} = \frac{\delta x}{f_2 W \mathrm{K}} \tag{4}$$

After to integrating linearly (4) in x-direction the density takes the form:

$$\rho(x) = \rho_0 + \frac{1}{f_2 W \mathrm{K}} \int_{x_1}^{x_2} \delta x dx \tag{5}$$

Where W= ζ_2- ζ_1 is the width of the test object and ρ_0 is the fluid density at the reference temperature T_0. For an ideal gas at constant pressure and assuming the Gladstone-Dale relation with the approach of small deviation angles, the temperature can be expressed as:

$$T = \frac{\rho_0}{\rho} T_0 = \frac{n_0 - 1}{n - 1} T_0 \tag{6}$$

Further details are found in [5],[6],[7],[8].

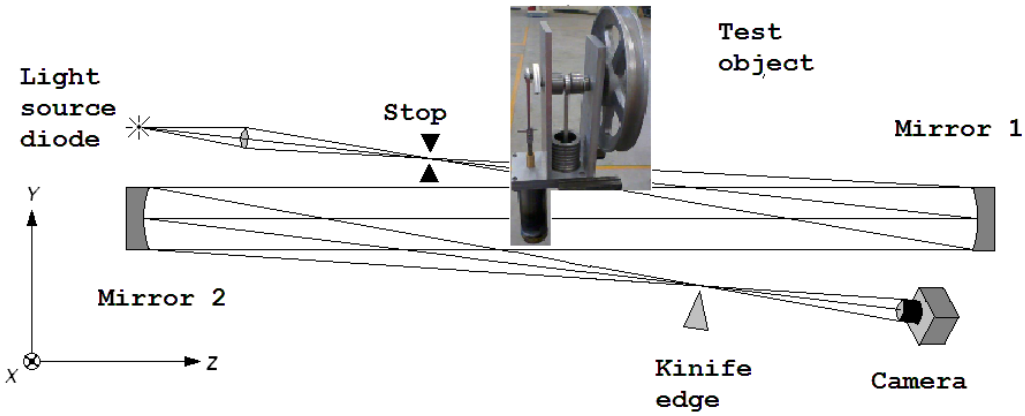

Figure 1. Z-type Schlieren setup with the Stirling engine as test object located in the half position between the two mirrors.

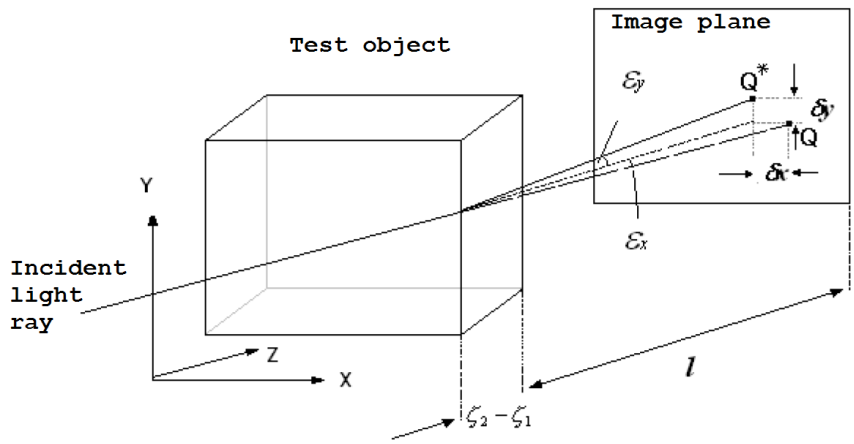

Figure 2. Ray pass through a transparent media l is the distance between the test object and image plane position.

2.2 Stirling engine

The Stirling engine is a closed cycle device with the same theoretical efficiency as the Carnot cycle which has four isentropic processes given by: Isothermal expansion between states 1-2, isochoric process states 2-3, in this process heat at T_H is absorbed by the regenerator changing the gas temperature at T_C. Isothermal compression states 3-4 at T_C,, and isochoric processes states 4-1, in this process the gas temperature is increased from T_C to T_H when gas pass through the regenerator in inverse direction as the 2-3 process as shown in the diagram depicted in figure 3, [3],[4].

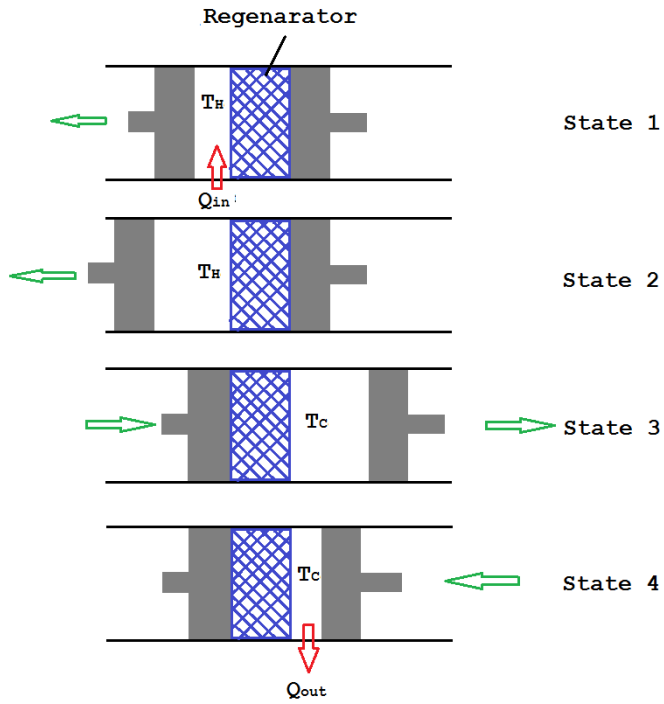

Figure 4 Process in the Stirling cycle

3. EXPERIMENT

In this research the Schlieren Z-type shown in figure 1 was used. The parts of the system and how it works will be explained bellow. A white light LED (Light emission diode) was used as a light source, using a pupil to get only a small part of the light due to its spherical form of propagating. This light beam is a collimated by the mirror 1 and then the second mirror of the system concentrates it into the focal plane of the setup. Then the light beam expands to arrive at the image plane of the setup as shown in figure 3. In the focal plane a knife edge is located with the purpose to cut the no deviated light rays and allowing its pass to form images in intensity scales from dark to bright. The intensity images have the information about the changes in x-direction of the refractive index of the test object. The Stirling engine was located in the middle of the Z-type Schlieren system, locating the cylindrical hot surface of the engine in the visualization area of the setup. The air-butane flame was used to heat the cylindrical hot surface of the Stirling engine. The image plane captures the gradients in intensities of the refractive index as explained before. The experimental setup has a 50mm of focal length which allows forming the image at the image plane. The information was captured acquiring 52.4 frames per second (fps) at a spatial resolution of 480x752 pixels, using a CMOS sensor which saved it in an avi format video file. In this work three experiments were accomplished, in which were captured 1000 snapshots in each one of them. A reference image was taken before to start the experiments. In the process of the information the avi file was cut in consecutive images in .mat format using Matlab code. The images were processed to get the gradient of the refractive index of the object in form of intensities gradients. Then the density fields were obtained to finally obtain the temperature fields using equations (3)-(6).

4. RESULTS

The results are shown in form of Schlieren images that represent the density gradients. In fact the Schlieren images of the convective hot gases allowed obtaining the temperature fields. First are presented the temperature gradients snapshots of the convective hot gases caused by the combustion in the flame. These Schlieren images are presented in a gray scale intensities. Temperature fields obtained from the experimental Schlieren images processed in Matlab are shown in a scale of color intensities, so that going from room temperature to hot temperatures is equivalent to going from blue to red color. The images in these figures are shown in the xy-plane that represents the full field of the density gradients and temperatures. In figure 5 raw images directly taken from

the Z-Schlieren setup are shown. In figure 5, a) corresponds to the reference images without test fluid, only with the atmospheric air at room conditions, b) and c) correspond to images when the cylinder is heating with the butane air mix flame, which represent the heat transfer in turbulent fluid flow. Fig. 5 d) corresponds to convective heat transfer toward the atmosphere, without flame. As can be seen from figure 5 b), c) and d) the Schlieren technique is a powerful optical test probe due to easy visualization and fast form to get information from the raw images.

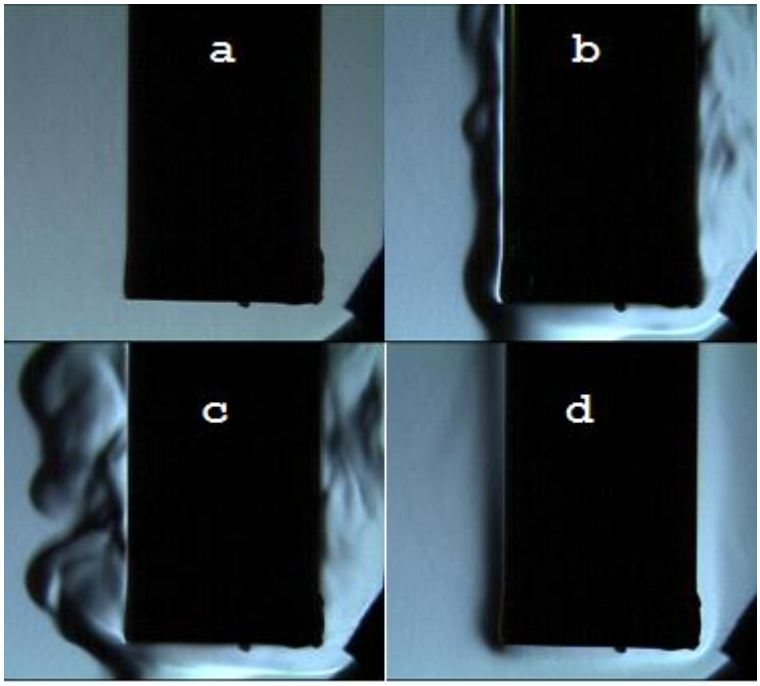

Figura 5. Schlieren raw images directly obtained from the experiment, a) reference image without flux, b) and c) forced convection heating the cylinder with the flame, and d) natural convection cooling the cylinder at room temperature.

Figures 6 a) and c) show images during the flow heating of cylindrical surface with premixed air butane flame after processing the raw Schlieren images applying Matlab algorithms referred to the equations (3) - (6). The process of these figures in Matlab is $Im_{fluid\ flux}$-$Im_{referencia}$. These figures show only the refractive gradients caused by the flame temperature [1]. This was used to remove the intrinsic noise from the Schlieren setup. Figure 6 e) shows the same process as in a) and c) but without flame, only the heat transferred by natural convection of the heated cylindrical surface was observed. Figure 6 b), d) and f) show the temperature field images obtained after integrating linearly figure 6 a), c) and e), respectively. As can be seen the integration of the Schlieren images was accomplished in zones where the temperature gradients were well defined. Figure 6 b), d) and f) show the qualitative behavior of the temperature. Figures 5 and 6 show how the heat is transferred to the cylindrical surface and from the cylindrical surface to the atmosphere.

In order to get more information about the temperature in quantitative manner, chromatic crayons were used as shown in figure 7. By using this procedure was possible to known the punctual temperature on the heated surface, and were estimated the starting and operating temperatures of the Stirling engine. The starting measured temperature of the engine was comprised between T=250 and 300°C, and the operating temperature reached T = 600°C.

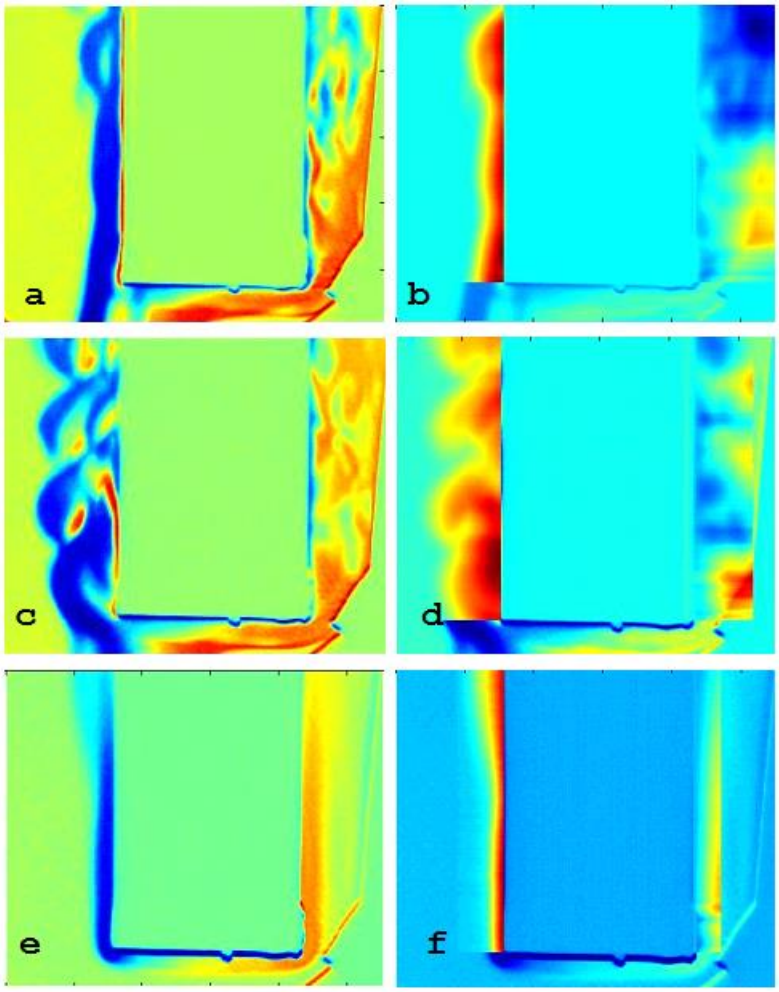

Figure 6. a) and c) are the Schlieren images in intensities of the heat transfer from the flame to cylindrical surface, subtracting the reference image. e) represents the cooling of the hot cylindrical surface by nature convection. b), d) and f show the temperature distribution of the temperature gradients.

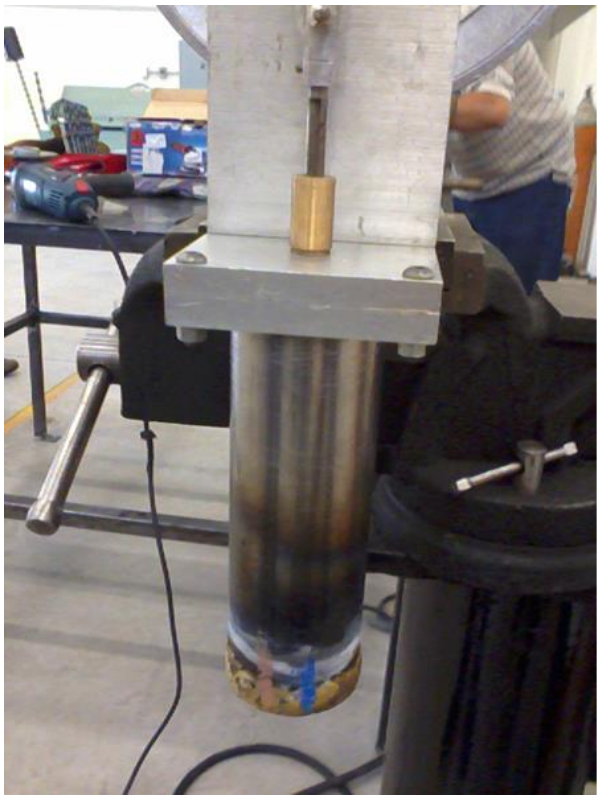

Figure 7. Stirling engine cylindrical surface showing two crayon marks one for measure temperature of T =250-300°C and the other for T = 600°C (blue color).

5. CONCLUSIONS

In this work were found interesting results about the temperature gradients and temperature distribution in a real Stirling engine. For this purpose the robust and full field Schlieren optical technique was used. Furthermore a punctual temperature was obtained using chromatic crayons in order to get detailed information about the temperature on the hot surface of a real Stirling engine. So with the use of the Schlieren technique and the chromatic crayons was possible to know more about how is the heat transfer in a real Stirling engine. The results of this research also showed that there is a lot of waste of heat during the work of a Stirling engine. In the future work, after to confirm these results it is possible to know using these techniques how to make more efficient the heat transfer in real Stirling engines.

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