"Eppur se muove", but, we do not understand how

ISSN 1870-9095

José Joaquín Lunazzi, **Antonio Marcos de Souza**
Institute of Physics, Campinas State University, Rua Sérgio Buarque de Holanda, Nº. 777, C.P. 13083-859, Campinas-SP-Brazil.

E-mail: lunazzi@ifi.unicamp.br

(Received 12 December 2020, accepted 23 February 2021)

Abstract

We present more considerations on how the Crookes's Radiometer works, a very didactical experiment, deepening and continuating previous disquisitions. The many formats that its vanes may have are considered for a better understanding of the many possible situations arising, and of its complex aerodynamics and thermodynamics. We see the similarity of this case to some ones in the history of science and engineering which showed that a presumed knowlegde lacked a better explanation.

Keywords: Optics Education, Light Force, Radiometers.

Resumen

Presentamos consideraciones adicionales sobre como funciona el Radiometrpo de Crookes, un experimento muy didáctico, profundizando y continuando anteriores disquisiciones. Consideramos los diversos formatos que sus paletas podrían tener para una mejor comprensión de las muchas situaciones que serían posibles, y de su compleja aerodinámica y termodinámica. Vemos una similitud de este caso con otros de la historia de la ciencia y de la ingeniería que mostraron que un conocimiento daco como establecido requería una explicación mejor.

Palavras chave: Enseñanza de la Óptica, Fuerza de la luz, Radiómetros.

I. INTRODUCTION

The Crooke's radiometer is a device which shows the presence and the intensity of light radiation coming from an intense source. It consists of a glass bulb under partial vacuum with four metallic vanes equally spaced fixed on a central glass semi-tube which lies over the fine point of a vertical metallic stem. Each of four thin vanes has a black and a white side equally orientated. It is well known in USA, and cheap, not so in Latin American countries. Its easy functioning hides the fact that his functioning lacks understanding, even more than one century after its first demonstrations. For most observers who knows physics it turns in an opposite direction than it should be. No precise calculations can be argued that demonstrates a proper theoretical interpretation. Maxwell, Reynolds, and even Einstein tried to explain the pushing effect but it still remains under discussion.

We consider that is very didactic to show to the students what physics still does not explains. Not that we try to teach that physics ignores much subjects, but that some subjects were left unconsidered in the race for some momentary prize. Water, for example, the fundamental substance in our life, was dismissed in favor of deuterium due to the nuclear race. It is so that the Mpemba effect, that of warm water freezing in some conditions faster than if it were cold, known since three thousand years, does not has an explanation until now. The Tacoma Narrow Bridge's history is another example of something that was considered entirely analyzed and solved, while it was not. In this article we comment on some elements which makes difficult the interpretation, and some others that should be considered to get a final solution.

II. CONSIDERATIONS ON HOW THE MOVEMENT IS GENERATED

When we try to understand not only the static pressure but the force that makes the movement on the vanes through the electromagnetic or quantum theories, the subject becomes difficult. The movement itself, then, involves a complete revolution inside the bulb, something that we do not find being treated in the bibliography, were it considered only the initial moment of movement transfer. Worrall (1982) [1] made a complete historical analysis to conclude that no theoretical explanation was already satisfactory. Which elements help to understand the generation of the movement? As it is described in the bibliography cited by him, the black vanes convert the incident radiation in heat more than the white ones, making greater agitation on the air close to them. It is possible to think in ascendant air currents influencing the movement, but it is clear that a greater force is the more important one. Nonetheless, the ascending air currents should be responsible for a vertical temperature gradient in the air which maybe influences also the vane temperature but which, in our opinion, does not influence the movement.

The ascendant air current cannot attract the vane because on the opposite side there is the air which, being much less dense, is effectively attracted towards. One of the elements not helping to understand is that vacuum is needed for the movement to happen, if more air is present, it does not happen. We can think that more air does not increases the number of collisions between the hot black surface and the air, but that more energy becomes then necessary to overcome the air inertia at this denser medium. At the first moment a delay to start the movement happens that could be thought to be inertial, but inertia coming from the vanes and air mass never impeach the movement, it only makes it slower, that is why we think in friction as an important element to be considered but this is not cited in the bibliography. We recently made an article including the subject [2]. Many didactical elements can be applied to the demonstration and one that makes grow even more the curiosity of the students is the influence of non-radiation heat on the movement. Heating the bulb, the vanes acquires the same rotation sense which is obtained with light or infra-red radiation, while cooling it makes an opposite rotation. By heating the air inside, more energetic collisions happens in the black side of the vanes, receiving more pushing. We can see that in Krasnow [3].

Gibbs (1997) [4] analyzes the process based on a model of an ideal gas in thermal equilibrium and with instantaneous transmission of pressure. We do not consider thermal equilibrium because there heat on the black side of the vanes which is dissipated during the movement, there is cooling through the glass bulb and the vane cools within each cycle. Figure 1 shows our view of the phenomena.

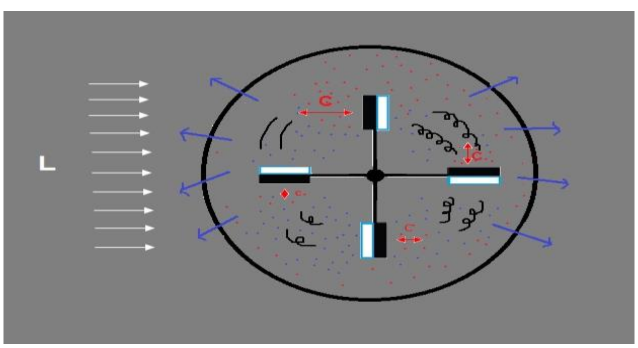

FIGURE 1. Representation of thermodynamics and aerodynamics elements in the process.

Cold and hot air molecules ar represented in blue and red, respectively, in greater or lesser concentration, to indicate the gradate variation of temperature within the gas. L indicates the impinging light, C, c, indicates the existence of collisions that generates the pushing of the vanes, diminishing along the round path. The blue arrows exiting the bulb represent the cooling of the internal air. The spiral curves indicates the probable presence of turbulences.

Neither we think that the pressure is instantaneously transmitted through the rarified air uniformly within the whole bulb, air currents and nonlinear processes may be present. Aerodynamics is a complex process. It is interesting to know that at the beginning Crookes believed that no force could exist on a reflective side. But no movement was verified in a Crooke's radiometer being pushed from the white side of its vanes. One element to be considered is the different kind of bright vanes's surfaces.

Usually, they are not reflective but white, making some difference on the effect. The measurements of Lebedev (1901) [5] of the torsion resulting on a thin wire with two vanes, one reflective and the other partially reflecting, validated the expression for the force being greater for greater reflectivity: Neiter

$$F \propto (1+R)\,. \tag{1}$$

A similar improved experiment by Nichols (1901) [6] verified push from the reflective side being greater than on the absorbing side, but in a single static element, not in rotating vanes. On the other hand, Gold (2003) [7] denies the effect of pushing on the reflective side arguing that if a mirror sends back the light it received, cannot take energy from it. In consequence there would be no inverted movement in case of much greater vacuum. Horsley (2011) [8] shows the electromagnetic treatment for the case of light reflected by a moving mirror but not being pushed by the light. Mansuripur (2012) [9] consider that a change in the photon's frequency could be observed on the reflected light from which to evaluate the mirror's received pushing force. In an experience illuminating a 5 mg object. Matsumoto (2015) [10] also assures that even quantum mechanics may enter the discussion. No rotation was experienced at greater vacuum, which should end the contradiction. We do believe that this is because of the friction at the axis. One first attempt could be done of reducing it by shaking, then having the reduced dynamic friction value, similarly as we demonstrated in an ordinary radiometer. There is a delay from the moment of the illumination and the starting of the rotation not mentioned neither measured nor explained in the literature. We understand that the black surface stays heating and increasing the pressure until it is enough to generate a torque overcoming the static friction. To explore this, during rotation we illuminated with an intensity a little smaller than that necessary to start the movement. After that, we obturated on the light until the movement stopped and releasing the light again, we just made a soft touch on the bulb that provoked a small oscillation of the vanes and it started to rotate again![11]. The influence of friction on the process was then made clear, the oscillation of the vanes making the transition of static to dynamic friction. We found friction being considered in the experiment [12] by measuring the time in which the vanes stop rotating, its deceleration being caused by the frictional force, but there could be a theoretical difference due to considering the dynamic frictional coefficient being the same all over the rotation process, at different velocities. Its constancy may not be true, instabilities may be present even in a continuous movement.

If this is not enough, the experience should eliminate friction being made in no weight conditions, as in a space station. Righi and later Bertin and Garbe (1877) [13] tried to avoid friction by putting a bulb with the vanes fixed on it to float while illuminating. We do not consider the validity of such an experiment because it is neglecting an equivalent friction arising from the water being in contact with the bulb.

On the contrary, a historical experiment that influenciated researchers in 1876 overestimated the roughness between the rarified air and the bulb. Woodrof (1968) [14] describes an experiment by Schuster trying to identify the influence of internal forces (he names as "radiometric") due to atomic collisions, separating them from the external light forces. He suspended the whole radiometer to observe some rotation when illuminated, with null result. This procedure assumes that the vanes transfers to the radiometer its movement but this can only be a partial transference determined by the axis friction, and it may be evaluated to not be considered negligible according to the sensitivity of the experiment.

Krasnow [15] gives a good report of the relationship between pressure and rotation. At pressures higher than its optimal value, the rotations starts to diminish and cease, not being possible to perform the experiment in ambient pressure. We consider this to be due to the fact that more molecules in the air does not increase the number of collisions happening, but the inertia to start the movement by displacing more air impeaches it.

We pay attention to the fact that the great development of optical tweezers did not benefit our knowledge of this macroscopic phenomenon. Let us make some observations: Jovanovic (2009) [16] made an analysis of light forces on particles (radiometric forces being named as photophoretic) which is interesting because, while the positioning of particles by means of light was much developed leading to the field of optical tweezers's applications, its extension to macroscopic objects was not yet considered, as also claimed by Chen (2020) [17]. The cases indicated could be applied to understand the Crookes's radiometer, and we see there the role that thermal conductivity appears to have. Another element to be considered is the thermal conductivity of the vanes, especially of the dark and bright layers. It should always be indicated if the shiny side corresponds to a reflecting, or to a white layer, and why one or another.

III. DIFFERENT VANES FORMATS

The edge extension could be an important factor, and there are many proposals of vanes that increase it, but we did not found references to more experiments on that sense, and connected to its theoretical explanation that could clarify our doubts. Wolfe (2015) [18], employed horizontal vanes.

He analyzed the presence of creep forces due to porous edges as formulated by Reynolds in 1874 and those formulated by Einstein in 1924, but without a precise agreement between theory and experiment. Scandurra (2008) [19] explains the Einstein's forces and suggests a holed dark vane which would be much more efficient, but, to our knowledge, that was never experienced. Chen (2020) [17] experienced a cylindrical curved gold leaf, a single laying element, obtaining a surprising inversion of the pushing. It demonstrates once more the importance of the air forces, including convection. And the lack of experiments using curved vanes with horizontal or vertical axis. Bekker (2020) [20] experiences different kinds of nanodisks. Jesensky (2016) [21] demonstrates the light pressure with a setup working at atmospheric pressure, not in a vane but in a vibrating element. We show in Figure 2 new proposals that may help to evaluate better the edge and aerodynamical effects.

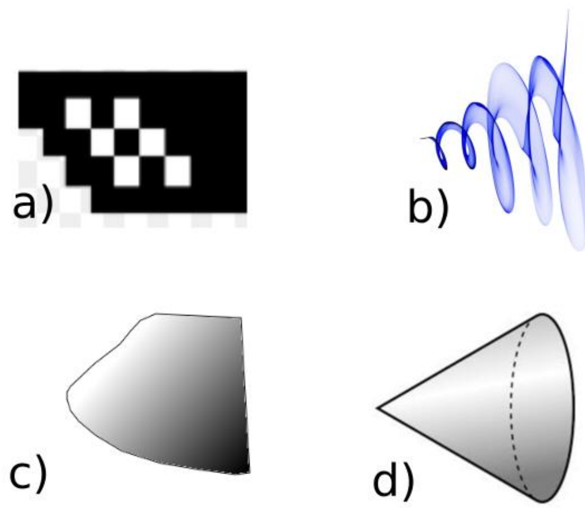

FIGURE 2: Four models of vanes. a) Holed. b) spiral. c) Aerodynamical in Jumbo airplane format. d) Conical.

IV. NOBODY KNOWS, THE TROUBLES I'VE SEEN

According to graduate courses the device must be rotate being pushed from the white side, because the momentum change should be double in that case, making a mechanical analogy that does not fit with the wave character of light, which cannot be considered as a jet of diminute particles as Newton conceived. It is hard to understand, due to the principle of conservation of energy, how any process could revert the direction of rotation. The device's functioning would better comprehensible with a concrete equationing of the value of the energy being transferred by the electromagnetic radiation to a surface, and of the whole system, being confirmed through measurements. This problem includes more than radiation and thermodynamics, but the displacement of the surface being pushed and nonlinear aerodynamics. It brings a remembrance of the Tacoma Narrows bridge failure [22, 23], a case apparently technically solved in all its aspects, but that an aerodynamical not considered effect caused its downfall. It looks like if the Crooke's radiometer entered into the same situation as the Mpemba effect [24, 25], a simple experiment not elucidated until now.

V. CONCLUSIONS

We reassured the idea that, in more than a century a small and popular apparatus was not sufficiently studied such that its functioning could be understood in consent.

We hope to see solved the theory and its experimental matching, to know the experience with new format of vanes, or without weight on the vacuum of sidereal space, confronting the different ideas that we mentioned in this article. And we believe to have showed that friction cannot be dismissed. Our analysis follows a path without defining a solution, opposing a tradition of asserting that everything in physics is under knowledge and control, a pedagogical tool that we believe increases the capability of thinking of the students. As in the Mpemba experiment, this one can be very hard to understand and may enter the field of non-linear treatment.

ACKNOWLEDGEMENTS

The authors acknowledge to the Brazilian post-graduation program on the teaching of sciences PECIM of Campinas State University where this work is being developed. We acknowledge to the physicist Mark Anthony Barrios Mamani for its work on editing video. To Marko Perestjuk for his indication of Ref.12. To André Luiz Polano for helping in idiomatic questions. "In Memorian" to Prof. Carlos Alfredo Arguello, founder in 1978 of the Laboratório de Óptica do Instituto de Física da Unicamp, where this work was made. To Coordenação de Aperfeiçõamento de Pessoal de Ensino Superior-CAPES-MEC for keeping free access to many important scientific journals. To Cornell University-USA for keeping the repository of articles Arxiv giving free access to millions of articles on Physics and Physics Teaching. To the social networking site Research Gate, which makes possible the reading of articles and projects and general communication between its members. Thanking to depositphotos's archive for the drawing "blue spiral".

REFERENCES

[1] Worrall, J., *The pressure of light: the strange case of the vacillating 'crucial experiment*, Studies in History and Philosophy of Science Part A **13**, 133-171 (1982).
[2] Lunazzi, J. J., de Souza, A. M., *The Crookes's Radiometer is a light vane,* Revista Brasileira de Ensino de Física **43**, e20200357 (2020).
[3] Krasnow, B., *How a Crooke's radiometer works*, channel, Applied Science: https://youtu.be/r7NEI_C9Yh0 visited on December 20th, 2020.
[4] Gibbs, P., *How does a Light-Mill Works?* unpublished manuscript, http://math.ucr.edu/home/baez/physics/General/LightMill/light-mill.html visited on December 20th, 2020.
[5] Lebedev, P. N., *Experimental examination of light pressure*, Ann. Phys. **6,** 433 (1901).
[6] Nichols, E. F., Hull, G. F., A *Preliminary Communication on the Pressure of Heat and Light Radiation*, Phys. Rev. **13**,307 (1901).
[7] Gold, T., *The solar sail and the mirror*, Center for Radiophysics and Space Research, Cornell University. Unpublished manuscript https://arxiv.org/abs/physics/0306050 visited on December 20th, 2020.
[8] Horsley, S. A. R., M. Artoni, and G. C., *La Rocca. Radiation pressure on a moving body: beyond the Doppler effect*, JOSA B **29**, 3136-3140 (2012).
[9] Mansuripur, M., *Solar sails, optical tweezers, and other light-driven machines*, In: Tribute to Joseph W. Goodman. International Society for Optics and Photonics, p. 81220 (2011).
[10] Matsumoto, N., *et al*., *5-mg suspended mirror driven by measurement-induced backaction*, Physical Review A **92**, 033825 (2015).
[11] Lunazzi, J. J., Souza, A.M., *Energia Mecânica - Radiômetro de Crookes (Cata-Luz) - Eliminando o Atrito Estático*, (2019): https://www.youtube.com/watch?v=RhkxIq7DK0Q visited on December 20th, 2020.
[12] Bächle, P., Körner, H., *Physics laboratory for beginners, "And yet it turns, the light mill"*._University of Konstantz, https://ap.physik.uni-konstanz.de/projektpraktikum/PP2008/ Visited December 26th 2020.
[13] Bertin et Garbe, Ann. de Chim. et de Phys, **11**, 67 (1877).
[14] Woodruff, A. E., *The radiometer and how it does not work*, The Physics Teacher **6**, 358-363 (1968).
[15] Krasnow, B., *How a Crooke's radiometer work*, channel "Applied Science": https://www.youtube.com/watch?v=r7NEI_C9Yh0 visited on December 20th, 2020.
[16] Jovanovic, O., *Photophoresis—Light induced motion of particles suspended in gas*, Journal of Quantitative Spectroscopy and Radiative Transfer **110**, 889-901 (2009).
[17] Chen, G.-H., Wu, M.-Y., Li, Y.-Q., *Pulling and lifting macroscopic objects by light*, Unpublished manuscript arXiv preprint arXiv:2008.04074, (2020). Visited on December 20th.
[18] Wolfe, D., Larraza, A., Garcia, A., *A horizontal vane radiometer*, Experiment, theory, and simulation, Physics of Fluids **28**, 037103 (2016).
[19] Scandurra, M., *Enhanced radiometric forces*, arXiv preprint physics/0402011 (2004).
[20] Bekker, C. J., Baker, C. J., Bowen, W. P., *Radiation pressure-tunable photoluminescence and upconversion*

lasing on a chip, Unpublished paper arXiv preprint arXiv:2007.12472 (2020). Visited on December 20th, 2020.
[21] Jesensky, G. *et al*., *A simple table-top demonstration of radiation pressure on a macroscopic object*, arXiv preprint arXiv:1606.01919 (2016).
[22] Olson, D. W., Wolf, S. F., Hook, J. M., *The Tacoma Narrows Bridge collapse*, Physics Today **68**, 64–65 (2015).
[23] *Why the Tacoma Narrows Bridge Collapsed***,** https://www.youtube.com/watch?v=j-zczJXSxnw https://www.youtube.com/watch?v=mXTSnZgrfxM Visited on December 20th, 2020.
[24] Mpemba, E. B., Osborne, G., *Cool?*, Phys. Educ. **4**, 172 (1969).
[25] Lu, Z., and Oren, R., *Nonequilibrium thermodynamics of the Markovian Mpemba effect and its inverse,* Proceedings of the National Academy of Sciences **114**, 5083-5088 (2017).