On the phenomenon of a light sphere in an inclined air jet

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Abstract: The article offers an explanation of the phenomenon of suspension of a light sphere in an air jet. The incompleteness of the widespread explanations based on the Bernoulli equation and the Coanda effect is shown. An explanation including the existence of a stall zone has been proposed and it has been shown that the Bernoulli equation and the Coanda effect have an indirect effect by shifting the stall area. The validity of the proposed logic is partially proved by comparing the constructed flow picture with the actual one obtained by schlieren photography.

Keywords: *turbulent jet, hydrodynamic levitation, Bernoulli equation, Coanda effect*.

1. Introduction

Somewhere in the early 1990s, on a visit to the AFA "G. Benkovski" was the President of the Republic of Bulgaria, Dr. Zh. Zhelev. As is usual during such visits, the officials get acquainted with the training facilities of the School. The Aerodynamics Laboratory was represented by the Head of the Aerodynamics Department, Colonel Krassimir Dimitrov, a first class military pilot, an instructor for all types of conditions. At the presentation of the laboratory, Colonel Dimitrov demonstrated the hanging of a ping-pong ball in a inclined air jet. The author of this article has shown this experiment many times, including to his children, and the usual reaction is, "Well, so what?" However, Dr. Zhelev, as a man of scientific thinking, was sincerely interested in the paradoxical behavior of the ping-pong ball and asked Colonel Dimitrov: "Could you explain this phenomenon to me, Mr. Colonel, but somehow simpler, as for a head of state? " Krassimir Dimitrov is a man with a sound judgment of circumstances and people, and therefore his answer, "In science, Mr. President, there are no royal roads." was by no means a show of disrespect, but result of his natural sense of humor, his broad general culture, and a hint to the Dr. Zhelev's scientific background. Of course, as a scientist-philosopher, Dr. Zhelev knew the famous phrase attributed to Euclid that there are no royal roads in geometry, he burst out laughing and did not stop laughing until he and his entourage left the aerodynamic laboratory.

After this sketch was thoroughly and irrigatingly discussed at informal meetings of the department, the question somehow arose: "Do we really know the explanation of this phenomenon?". Of course, the standard explanations are widely known, but a more detailed analysis raises a number of questions. Since then, the author of this article has repeatedly returned to them and become convinced that this is one of the cases of popular misconcepts in aerodynamics [1].

2. Explanation of the phenomenon of a light sphere in an air jet

2.1. Description of the phenomenon

A ping-pong ball is placed in a vertical air jet (for example, from a hair dryer). The jet impacting from below "holds" the ball in the air, and since, unlike in Fig. 1, in the real experiment the jet is not visible, the ball appears to "levitate". It is intuitively clear that the pressure force from the jet balances the weight of the ball. The ball oscillates laterally, but does not fall out of the jet, but self-centers. If we start to tilt the jet, the ball does not fall, but up to an angle, for example of 45°, remains in the jet, which is surprising (Fig. 1).

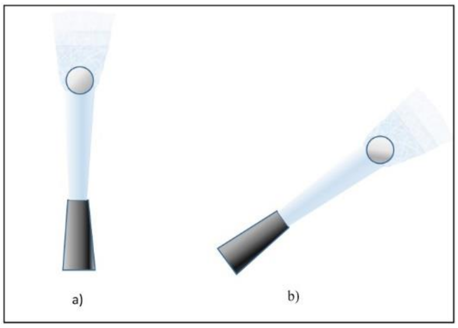

Figure 1. Light sphere in an air jet: a - vertical, b – inclined

A meaningful explanation of this phenomenon should answer the following questions:

- Why the ball does not fall when the jet is vertical?
- Why the lateral oscillations do not throw the ball out of the jet, but it self-centers?
- Why doesn't the ball fall off when the jet is tilted?

2.2. Existing widespread explanations

In some older publications [2] the suspension of the ball in the jet when the jet tilted is based on the direct applying of Bernoulli equation. When the jet is tilted, the ball moves to the side and the streamtubes of which the jet consists are deformed, as shown in Fig. 2. In the narrow part of the streamtube air velocity increases and according to Bernoulli equation pressure decreases, sucking the ball in the jet.

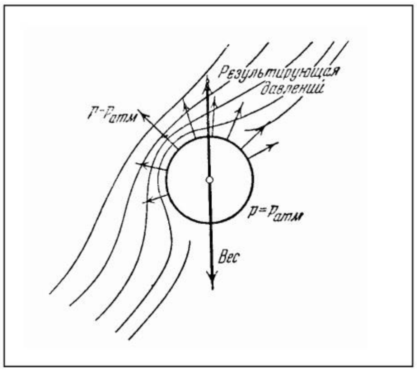

Figure 2. Explanation of the phenomenon ping-pong ball in an inclined air jet [2]

Such a flow picture, however, corresponds to an ideal fluid with no viscosity. In real air, in the back side of the sphere, the flow separates from the surface of the sphere and as such, this explanation is not correct.

In other sources [4] the explanation of the phenomenon under consideration is based on the Coanda effect . The effect of Coanda is that a free jet in a viscous fluid near bent surface adheres to the surface (Fig. 3).

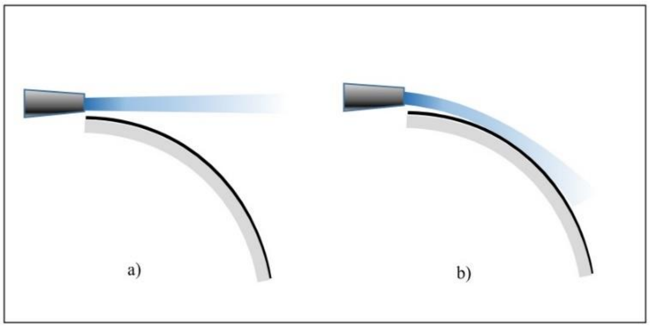

Figure 3. Coanda effect: a - jet in an ideal medium, b - jet near curved surface in a real medium

The explanation of the phenomenon under consideration, based on the Coanda effect, suggests that the jet adheres to the surface of the sphere. The jet bends (Fig. 3). If we think of the jet surface as a streamtube, we can apply the analogy between the behavior of streamtubes and rubber tubes [5]. When the rubber tube "bends", the cross-sectional area decreases, the speed increases, and according to Bernoulli's equation, the pressure decreases. The resulting low pressure balances the force of the weight and the ball remains sucked to the jet (Fig. 4).

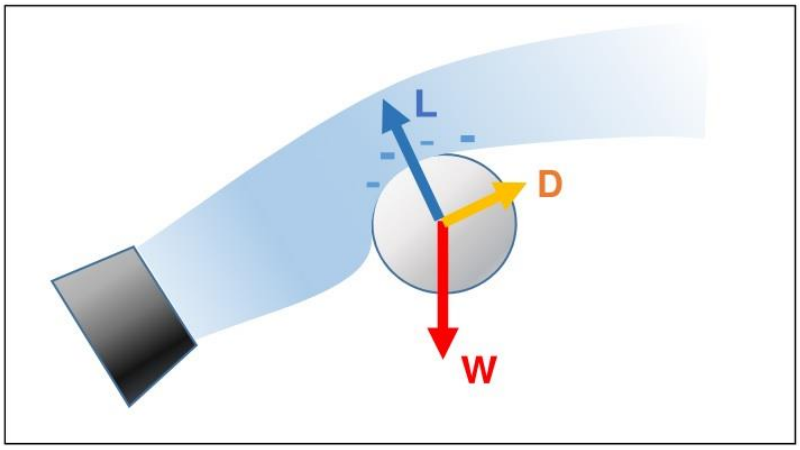

Figure 4. Coanda effect in case of a light sphere in an inclined jet

Indeed, with a jet of small diameter (compared to the diameter of the ball) this is the case (Fig. 5).

Figure 5. Light sphere "glued" to water jet due to the Coanda effect [3]

However, studies on the degree of manifestation of the Coanda effect at different ratios of jet thickness and sphere diameter [6] show that the jet adhere to the surface at ratios $\frac{h}{d} \leq 0.5$ (Fig.6). In the case of thicker jets, an initial pressure decrease is observed under the adhered jet, after which the jet separates from the surface. This leads us to think that the formation of a stall zone with reduced pressure should be taken into account for jets with a larger diameter.

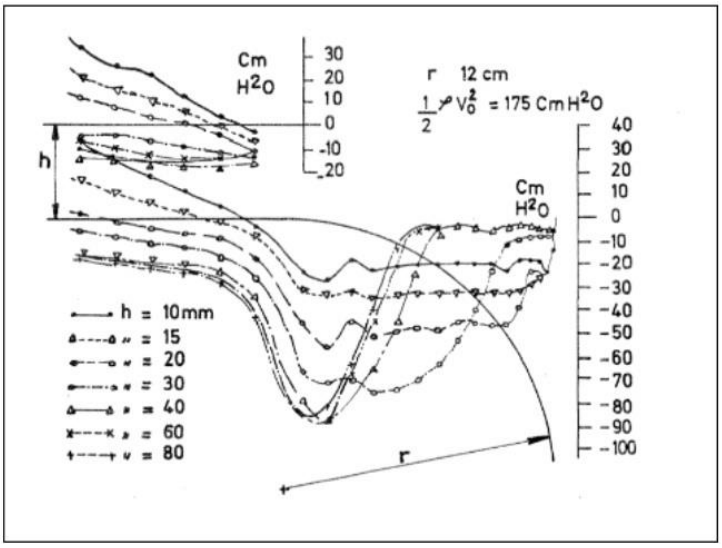

Figure 6. Jet thickness influence on the pressure distribution on a cylindrical surface [6]

2.3. Explanation taking into account the existence of flow separation zone

One of the factors to consider in the explanation is that the air jet is turbulent. The jet expands to establish inner pressure equal to the ambient one, and the airspeed decreases due to turbulent friction and the ejection effect on the ambient air (Fig. 7). The kinetic energy of the flow along the jet decreases. The Bernoulli equation, which is derived from the assumption of no viscosity, cannot be applied to the jet.

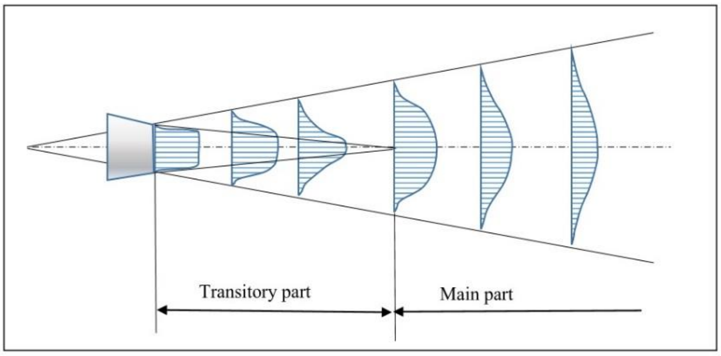

Figure 7. Mean velocity distribution in a free turbulent jet

Based on the assumption that the flow around the sphere implies the existence of a stall zone, the author offers the following answers to the above questions.

About the suspension of the ball in a vertical jet. When the jet diameter is small, the layer formed in the flow around the sphere has a small thickness and as such is subject to Coanda effect (Fig. 8a). There is no separation of the flow and the weight of the sphere is balanced mainly by the friction forces in the boundary layer. With a larger jet diameter, the layer surrounding the sphere has a large thickness and separates off in the rear (upper) part of the sphere. The increased pressure at the front critical point and the reduced pressure in the stagnant zone create a significant force of pressure drag, which balances the weight of the sphere (Fig. 8b).

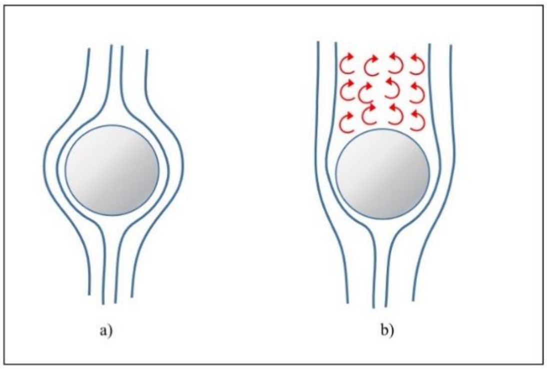

Figure 8. Vertical jet flow picture: a - for small diameter jet,
b - for a jet with a larger diameter

About the "self-centering" of the ball in a vertical jet. Turbulent disturbances in the jet cause transverse motions of the sphere. If we have a shift of the sphere to the right, the layer to the right of the sphere thins and due to the Coanda effect sticks to the surface of the sphere. The stall point on the right is shifted backwards. The layer to the left of the sphere thickens and the separation point moves forward. The asymmetry of the detachment zone creates a pressure force that returns the sphere to the neutral position (Fig. 9). In addition, the pressure difference is exacerbated by the uneven velocity distribution along the radius of the turbulent jet - at higher velocities in the central part, the pressure diminishing in the narrowing of the streamtubes is greater than the diminishing in the outer streamtubes, where the velocity in the undistorted jet is less.

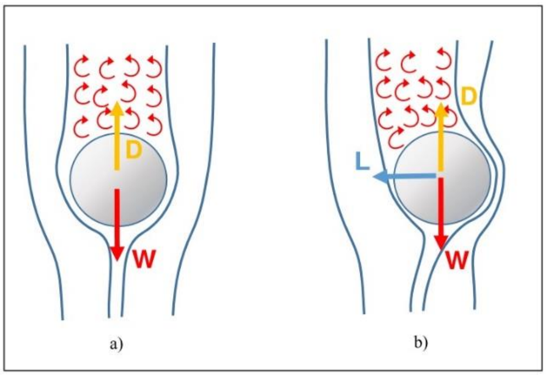

Figure 9. "Self-centering" of the sphere in a vertical jet

Regarding the suspension of the ball when tilting the jet. When the jet is tilted, the weight shifts the ball to the side and the logic of the explanation is similar. The weight of the ball is balanced by the sum of the lateral force and the drag (Fig. 10).

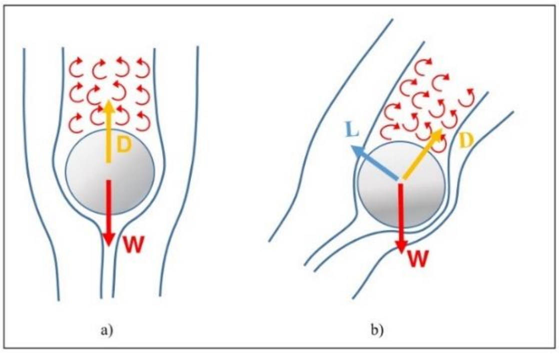

Figure 10. Зависване на сферата в наклонена струя

In order to test the above hypothesis, visualizations of the flow were used obtained by another author for a jet of hot air [4] with the help of schlieren optics (Fig. 11).

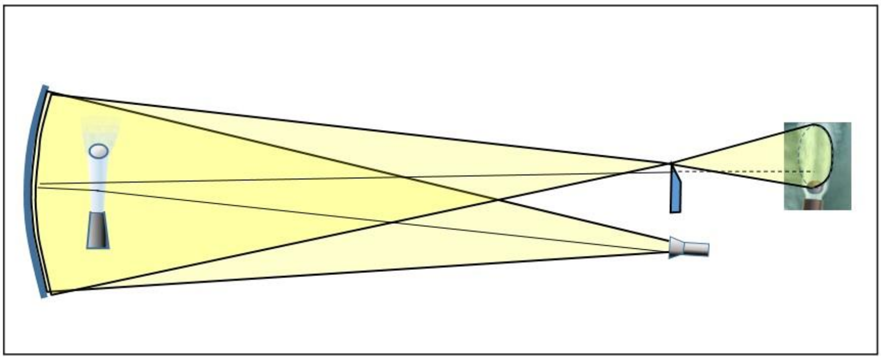

Figure 11. Schlieren optics with concave mirror

Fig. 12 shows the real pictures of the flow in the case of a sphere in a vertical and inclined jet.

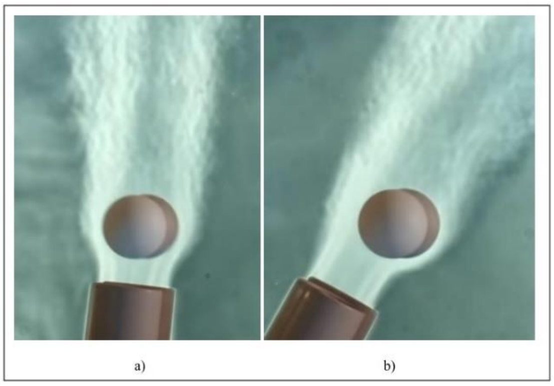

Figure 12. Schlieren photography of the flow in vertical (a) and inclined (b) jets [4]

3. Conclusion

The flow patterns shown in Fig. 10 were proposed by the author of this article before the photographs of Fig. 12 were available to him. The good similarity between the speculative picture of the flow and the real one in first approximation justifies the logic of the above considerations. Both Bernoulli equation and the Coanda effect have a place in the constructed explanations, but not directly, as in the standard explanations of the phenomenon of a light sphere hanging in an air jet. The key moment is their influence on the stall zone. And returning to the prehistory of this little application of the mental mechanics of fluids (MFD - the term was introduced by Doug McLean [1]), the author begins to think that the phrase "There are no royal roads in geometry" was uttered by Euclid with a thoughtful expression and look turned inward.

References

1. McLean, Doug (Doug J.), Understanding aerodynamics: arguing from the real physics, John Wiley & Sons, Ltd., 2013.
2. Фабрикант, Н. Я., Аэродинамика, ГИТТЛ, М:, 1949, 74
3. Hydrodynamic levitation - https://www.youtube.com/watch?v=mNHp8iyyIjo
4. Wolfgang Rueckner demonstrates the Coanda Effect. Harvard Natural Sciences Lecture Demonstrations channel on YouTube, https://thekidshouldseethis.com/post/demonstrations-of-the-coanda-effect
5. Савов, В. С., Използване на пластично-хидравлична аналогия за визуализиране на течението около крилен профил, сб. Доклади на НС на ф. „Авиационен“, 2014. 55-71
6. Kadosch M., Déviation d’un jet par adhérence à une paroi convexe in Journal de Physique et le Radium, avril 1958, Paris,1–12A