FIRE TORNADO

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ABSTRACT

The fire tornado is a special natural phenomenon that can be produced artificially, too. It is significant in the science centres because it is really spectacular and easy to show. Moreover, it models a large range of phenomena in physics, technology and chemistry. Therefore, it can be applied in experiments as well as in study groups. A popular device modelling the fire tornado has been developed by the Mobilis Science Center. The phenomenon can be presented in several ways. We can demonstrate the turbocharger, the gas turbine, the conditions of burning, and the chemistry of flame testing with it. A simplified explanation of the complex hydrodynamic processes taking place in a fire tornado will be also presented.

1. NATURAL PHENOMENON

Fire tornadoes are vertical fire whirls which can be observed in wildland, urban, and oil spill fires and volcanic eruptions. Fire whirls have also been called fire devils, fire tornadoes, and even firenadoes. Their size extends from 1 meter to 3 km in diameter. They can be observed easily due to the burning gases, ash and smoke. Fire whirls are rare but often devastating forms of fire which may occur for example when a stronger convection blows into a forest fire [1]. Due to the convection the fire is often transformed into a several meter high, rotating fire column. Fire whirls accelerate combustion, produce significant suction pressures and lifting forces, and can carry burning debris. Studying them is very important because of their great potential for damage when occurring in nature [2, 3]. The dynamics of the fire tornado is similar to other swirling atmospheric phenomena such as dust devils, waterspouts, and tornadoes [4]. Although fire tornadoes are rare and special natural phenomena, they can also be easily produced artificially. Fire whirls produced in laboratories are widely used for the investigation of the properties of the fire tornadoes [4-6]. Besides their scientific values, these whirls are very spectacular and therefore might be tools for motivating students for learning physics. In the following we are dealing mainly with these latter aspects of the phenomenon.

2. ARTIFICIAL FIRE TORNADO

Artificial fire tornadoes are very spectacular and therefore they are very popular experiments at physics demonstrations of Science Centres. Lots of films about them are available at Youtube [7] too. The phenomenon can be produced in several ways, it can demonstrate a lot of phenomena in physics and chemistry. The fire tornado can be easily demonstrated with the use of simple devices in the laboratory. We need a rotating disk, a small non-flammable bowl and acetone. (Any other easily flammable liquid is proper e.g. 96 % alcohol.)

Put a small bowl into the middle of a rotating disk. Fill it up with acetone (about 50 ml) then set it on fire. A slightly flickering flame of about 15-20 cm height appears. Starting to rotate the disk, nothing special happens. The height of the flame remains about only 15-20 cm. However, if the small fire column on the rotating disk is covered by a cylindrical wire mesh the flame will grow up and twist. Reversing the direction of the rotation the flame twists in opposite direction.

3. THE PHYSICS BEHIND

In spite of the popularity of the artificial fire tornadoes, their physical explanations available on the Internet are often insufficient and incorrect. The reason for this maybe is that the underlying physics is complex, the mathematical description of the phenomenon is not simple and the various approaches presented in the scientific literature are too sophisticated [5, 6]. However, in our opinion, taking into account the experienced properties of the artificially produced fire tornadoes a relatively simple approximate explanation can be given for them.

Our experiments - in accordance with the literature - have clearly shown that the development of a fire tornado needs a flame in which burning gases are ascending in a buoyant plume and the length of the flame can be increased by imposing rotation on this plume[1]. Keeping constant the rotation velocity and the burning rate a steady fire column is created. According to detailed investigations [3, 5] this hot column is rotating as a rigid body, therefore its azimuthal velocity increases proportionally with the radial distance measured from the centre of the whirl.

The phenomenon is analogous with the whirl coming to existence in rotating a water column (Fig.1.). Pour some water into a magnetic mixing bowl, scatter some tiny buoyant plastic granules onto the surface of the water and start to rotate the water. A conical whirl is appearing and is getting deeper and deeper, the tiny pieces are gathering on the side of the cone, some detach from the surface and move downward. Throwing more granules into the water, it can be seen that the pieces go closer to the axis of the whirl [8]. The water whirl corresponds to an upside-down fire tornado, where the tiny plastic pieces with low density correspond to the hot gases [9].

Fig.1. Water whirl Left panel: with plastic granules [photograph taken by the author in the von Karman Lab of ELTE]. Right panel: with coloured oil [10]

The two phenomena differ in the boundary conditions. While in the fire tornado the less dense warm air is flowing inward along a rigid ground, the whirl of the water column is generated in a cylindrical vessel of rigid wall. In the latter case the centrifugal force presses the water outward, which climbs on the wall of the cylinder and produces a conical surface. Therefore the height of the water is increasing with the increase of the radial distance and due to this a pressure gradient force rises, which balances the centrifugal force. The tiny plastic pieces are floating on the conical interface of the water and air. The tiny buoyant particles move in the water and in the air upward and downward, respectively.

The existence of the stable and steady rigid body-like rotation of the fire tornado can be supported by simple arguments. The reasoning can be accomplished either in inertial or in accelerating frames. The comparison of the two ways might be very instructive for secondary school students. In the frame rotating together with the flame

[1] According to our experiences at the beginning of the rotation the length of the flame increases with the increase of the angular velocity. However, reaching the angular velocity of 9 1/s, the fire column has not increased anymore; moreover it decreased a little, to the half of the height of the mesh. It means that a fire tornado has an optimal angular velocity to make the fire column be the highest.

column, the air particles are at rest due to the balance of the centrifugal and pressure gradient forces. With the notation of Fig.2. the forces acting on a cubic particle are:

$$F_{hidr.} - F_{cf} = 0$$

$$F_{hidr.} = p(r + \Delta r)\Delta r^2 - p(r)\Delta r^2 = \Delta p\, \Delta r^2$$

$$F_{cf} = \rho_{fluid} r \omega^2 \Delta r^3$$

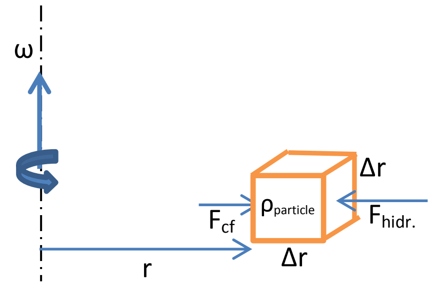

Fig.2. Air particle in the rotating flame column

It means that in the rotating fluid the pressure gradient is:

$$\frac{\Delta p}{\Delta r} = \rho_{fluid} r \omega^2$$

If there are density fluctuations in the flame and the density $\rho_{particle}$ of an air particle differs from that of its environment then a buoyant force acts on it. Due to this force the particle moves inwards (toward the centre of the rotation) if $\rho_{particle} < \rho_{fluid}$, otherwise if $\rho_{particle} > \rho_{fluid}$, it moves outwards. In the flame columns generally temperature fluctuations lead to the density fluctuations. Therefore as a consequence of the temperature fluctuations a secondary flow is generated in the flame column, hotter gas particles flow toward the rotation centre. This secondary flow strengthens the convection of the hot gas and lengthens the flame column. Due to the lengthening of the flame column its rotation is also accelerating. The effect is similar to the acceleration of rotation speed of figure skaters when they pull in their originally outstretched arms and decrease their rotational inertia.

A common misinterpretation of the phenomenon is based on Bernoulli's law. According to this explanation the pressure at the two sides of the mesh is different due to Bernoulli's law, therefore the air is flowing outwards at the mesh. This outflow is compensated by a descending flow along the mesh. This descending flow strengthens the upward motion of the air in the flame which - as a consequence of this - is lengthening and tightening. However, the Bernoulli-effect in this case is not strong enough to influence the flow largely. Because of the 1-mm thickness of the mesh and its relatively low azimuthal velocity air pressure difference is negligibly small between the two sides of the mesh.

A more correct interpretation may be the following: The inner surface of the cylindrical mesh drags the air so the flame starts to twist. The hot gases with small density flow up, as in a chimney, and they pull the flame up. The entrainment of the fresh air can occur only through the holes of the mesh.

4. THE APPLICATION OF THE FIRE TORNADO IN SCIENCE CENTERS

4.1. THE SOURCE OF THE IDEA

We have seen an artificial fire tornado for the first time at a demonstration performed by László Róbert Zsiros [11]. The video taken from it can be seen in his portal, szertar.com. His construction, the idea of which originated from Heureka Science Center in Finland differed from everybody's one.

Zsiros used a boxy shape trash can instead of the cylindrical wire mesh for covering the flame. This setup was also suitable to create a fire tornado.

2. SELF-DEVELOPED VERSION

In Hungary the Mobilis is the only Science Center which presents the fire tornado as an experiment in science-shows and roadshows as well. We have remade the model and it became safer, more spectacular and still portable.

The data of our self-constructed device are the following: the thickness of the wire of the cylindrical mesh is 1 mm, the diameter of the holes of the mesh is also 1 mm, and the centres of the holes are 3 mm far from each other. The diameter of the cylinder is 40 cm, its height is 1.1 m. The flame obviously grows up to the top of the cylinder.

Preparing the cylinder (Fig.3.). A flat highly perforated plate of 1 mm thickness was bended into a cylinder of 42 cm in diameter. The bending of the plate was to be made cautiously because during it high forces are arising in the plate. The edges of the plate were fastened by five screws.

Fixing the cylinder and the fuel bowl Three L shaped steal plates were fastened to the rotating disk leaving narrow gaps between the rim of the disk and the vertical part of the plates. The cylinder should be slipped into these gaps to fix it. The fuel bowl was fastened by three nails.

Safety conditions: The safety implementation is very important because most people are afraid of the experiment. After lighting up the acetone, refilling is dangerous and it is forbidden. The removing of the cylinder is also forbidden until all the fuel has burned out.

This self-made form has won a prize at an experiment innovation competition which was hosted by the OFI (Institute for Educational Research and Development) and the EvoPro Kft together [12]. These Institutes made a promise to develop a standardized production from this equipment which can be easily used for demonstrations at schools.

Fig.3. The self-developed fire tornado and the equipment

4.3. SCIENCE CENTER MODELS ABROAD

The Science Centre Singapore has got a 5-mhigh device. For this equipment - as it can be seen in the video [13] the air flow is ensured with strong blow. This form is very spectacular but it is not interactive. The construction is very complicated and not portable.

The Phaeno Science Center in Wolfsburg, Germany has got a more than 6-m-high equipment. This construction is one of the most popular experiments in Wolfsburg. The air flow is ensured by ventilators which suck up the air from the space above the fire column. [14]

There are fire tornadoes which work with upper ventilators in Poland at the Copernikus Science Center (Warsaw) and in England at The Magna Science Adventure Center (Rotherham) too. Each of these pieces of equipment is several meters in height and is not portable.

5. METHODOLOGICAL AND DIFFERENT MODELING OPPORTUNITIES

5.1. WHY DOES THE MOBILIS SCIENCE CENTER USE IT?

The Mobilis Science Center has a unique subject in experiments, it focuses on car-vehicle-transport. The other Hungarian Science Centers are dealing universally with natural sciences and they append some concrete natural or technical applications. The philosophy of the Mobilis is reverse. We show technologies from the vehicle industry appending natural science analogies and explanations. Mobilis is located in a 1200 m^2 building. We have got 70 interactive exhibition devices and present physics-laden science shows, roadshows. We have also led study groups. In science shows, we present and analyze, for example, the fire tornado.

5.2. UTILIZATION

The experiment models a reverse-acting gas turbine, where we can increase the burning by rotating the cylinder. The real gas turbines work in the other way. The burning engenders the rotation, for example in the case of the jet planes. It is similar to the turbocharger because it flows more air into the combustion chamber. A Science Center which focuses on the vehicle industry has to present these analogies as well.

It holds the opportunity of interactivity. It is suitable for a teacher-led demonstration, but only works in small groups; over seventh or eighth grade students can do it independently. The kids can do the cap filling and setting the fire, but putting up the cylinder is two people’s job. Doing the experiment needs an adult observer or a teacher. Scientific birthday can be held with it. There is a big demand for scientific birthday parties in our center. There the kids do experiments, they play and they can watch a special science show as well. The celebrated kid can rotate the candle on the cake, the fire tornado. It can be applied in chemistry lessons. We can recommend this experiment for chemistry lessons because we can demonstrate flame-dyeing. We can explain the conditions of burning. It can be applied in physics lessons. Hydrodynamics, convection, density, buoyancy, rotating movements can be explained with this experiment.

5.3. VERSIONS

Double flame. We put two fuel sources into the serving disk. One of them should be filled with acetone and the other with methanol with dissolved copper sulfate. After igniting the fuels green and yellow flames are growing up and twisting around each other. Flame-dyeing. Before pouring methanol into the fuel bowl, put some copper sulfate into it since the methanol dissolves the copper sulfate well. The copper ions will dye the flame to green. Without moving device. Instead of the cylindrical mesh a transparent, tight plastic sheet can be also used as enclosure of the tornado. As shown in Fig.4., a tangential gap should be left on the cylindrical sheet. The flowing gases of small density only get fresh air from this gap. The tangentially entrained gas turns the air inside the enclosure and the flame is twisted.

Turn-way sensitive. We make a cylinder from an expanded disc. Due to the shape of the holes, the effect of turning the disk to right and to left is not same. If it turns left, the air flows inwards and the burning is stronger, so the flame is lengthening. Reversing the rotation, the air flows out from the cylinder, the flame decreases to the third of its former length. 12 big ventilators turn the air. It needs 5 liters of acetone and a heat resistant pot. This experiment can he made only outdoors. The flame is twisting up to 4-5 m height (Fig.5.).

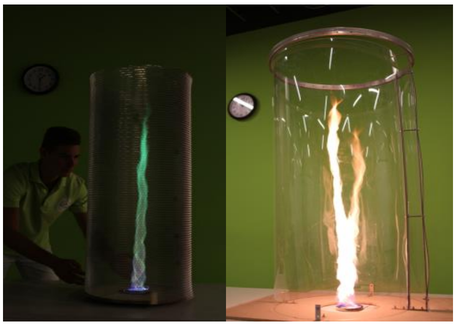

Fig.4. Left: flame-dyeing.
Right: without moving device

Fig.5. Left panel: The turn-way sensitive expanded disc. Right panel: with 12 ventilators

CONCLUSIONS

Natural sciences should be popularized in all possible places. We should go into the streets among those people who do not come to the science center and should explain them that science, physics is all around us and science can be exciting. All Science Centers have the task to teach the people in informal ways. The spectacular and extraordinary experiments raise attention; provide the possibility to give explanations in different depth and from different points of view. The Science Centre can help the teachers: gives ideas how to make simple devices. Moreover, it provides additional knowledge and special experiments that cannot be shown in a school.

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