Electrostatic deflection of charged droplets with asymmetrical injection: unexpected optimal design

Michael Retsky; Electron Optics Development Co., LLC; Trumbull, CT

Abstract

Continuous inkjet printers selectively direct charged droplets to the target medium or into a gutter for recycling by deflecting the stream with an electric field. While this is a well-known and mature technology, it sometimes is useful to revisit the underlying science. We have done this in the similar case of electron beam deflection and results are counterintuitive. Traditionally, to avoid the edge effects at the entrance as much as possible, charged streams have been injected symmetrically into the gap between two oppositely charged conductive plates. However we found that optimal deflection occurs when the stream is injected about 1/3 of the way toward the attracting plate. The stream can be quite wide - about 1/3 of the gap is acceptable. Under these conditions, deflection angles can be much larger than the 10 degrees or so previously considered maximum. For example it is possible to cleanly deflect a charged stream by up to 50 degrees or so. Optimal asymmetrical injection allows the stream to follow equipotentials so that the deflection force is normal to the trajectory and relatively uniform over the entire droplet avoiding break-up. There may be useful design advantages using optimal offset deflection technology in continuous inkjet printing.

Introduction

As it is widely known, there are two broad types of inkjet printing devices - *Drop-on-Demand* that produce ink only when needed and *Continuous* that flow ink droplets steadily but direct them to the target medium as needed or to a gutter for recycling. In continuous flow devices, the ink droplets are directed by applying electric charges to the droplets and passing them through an electric field provided by two conductive plates at different electric potentials. Deflection of charged particle streams is an old science dating back over 100 years to the first cathode ray tube. Even so, it is sometimes useful to reexamine mature technology to see if there are possible improvements that can be made.

Thousands of instruments and devices make use of electron or ion beams or a variety of other charged streams including charged ink droplets. As examples, these devices include electron beam welding, mass spectrometers, cell, bacteria or algae sorting in flow cytometers, electron microscopy, electron beam lithography including computer chip and mask manufacturing, electron beam computed tomography, ion beam milling, accelerators in physics research, nanodevice fabrication, and isotope enrichment for medical applications and for nuclear weapons. In virtually all these cases, somewhere the stream needs to be deflected as some integral part of the normal operation of the device. Deflection devices are ubiquitous in charged particle optics. There are two ways to deflect a moving charged particle – by passing it through either a magnetic field or an electric field that is normal to the path. Here I will restrict our discussion to deflection using an electric field.

Deflection of charged streams with electric fields

For electric field deflection, almost every textbook in charged particle optics shows the same standard derivation. It assumes the electric field between a pair of oppositely charged plates equals the applied voltage difference divided by the spacing. The effective length slightly exceeds the physical length. The field is assumed negligible outside the space between the plates. Therefore the force acting on a charged particle is zero outside the gap and constant within the gap. The particle is directed into the exact center of the gap to as much as possible avoid the fringe fields at the edges. According to the standard assumption, the particle experiences no force in the original direction of motion. Thus the beam envelope comprising a large number of separate particles has a straight line path before it enters the gap, a parabolic trajectory within the gap and another straight line trajectory after exiting the gap. The stream is deflected into an angle that is proportional to the applied voltage and also to the charge on the particle. The deflection varies inversely with the particle's mass. The deflection angle can be adjusted by varying either the applied voltage or the charge on the particles. In the case of electron or ion beams, the charge and mass are fixed by nature so the amount of deflection is controlled by adjusting the voltage applied to the plates. In the case of charged ink droplets, the deflection is usually controlled by adjusting the charge applied to the ink droplet.

How good is the uniform field assumption in electric field deflection and how accurate are the resulting expressions for charged particle trajectories? Deflection using this technology rarely exceeds 10 degrees or so since the deflected streams acquire aberrations that increase with the angle of deflection and width of the beam. I have been studying this subject for a number of years. It is a difficult subject because there is no simple closed form mathematical expression for the electric field in the vicinity of two electrically charged conductive plates. The fields are complex especially at the edges as indicated for the case of parallel flat plates as seen in fig. 1. It is small wonder that practitioners try to avoid coming close to the plates.

For an electron beam, as the angle of deflection increases beyond 10 or so degrees, individual electrons get deflected into different angles depending on where the electron is in the beam. For example, electrons closest to the positively charged plate will be deflected less than electrons that are in the center of the beam or electrons that are farther yet from the positive plate. That means that a beam that enters the deflection area round and parallel will not be round and parallel after deflection. In general such aberrations are only partially correctable and it will not be possible to finely focus the beam after deflection as well as the beam could be focused before deflection. These deflection aberrations are well-known limitations of deflection devices and electric field deflection devices in particular.

If instead of an electron beam, the stream consisted of individual ink droplets, the droplets might be pulled apart or different droplets will be deflected into different angles depending on their locus relative to the center of the stream.

Method to reduce electric field deflection aberrations

My investigations into this complex subject produced a simple and counterintuitive result [1]. Instead of injecting the charged particle beam directly into the center of the plate gap, it is far better to inject the beam offset toward the attracting plate. The offset is significant. The optimum offset will depend upon the specific geometry but overall, an offset of about 1/3 of the way toward the attracting plate is optimum. Also the beam diameter can be up to about 1/3 of the plate gap. Under these simple conditions, the deflection aberrations are reduced by a factor of at least 10-fold. In experimental conditions, when so optimized, it was not possible to detect deflection aberrations. A beam that was round and parallel when injected with the proper offset would exit into a new direction and continue to be round and parallel. The angles of deflection can be rather large. Angles of 30, 40 or even 50 degrees are possible without deflection aberrations.

The offset is large enough so that only half of the deflection gap is used. The plane of symmetry is a virtual ground and can be established with a grounded plate. The repelling plate is not needed. Thus only one of the deflection plates and only one of the deflection voltages are needed. The attracting plate is preferably shaped for optimal operation. This invention is described in US patents 5825123, 6232709, and 6614151. Design software is published in these patents.

How does this optimal deflection configuration impact inkjet printing?

What if any problems could be solved or what improvements if any could be made if such a deflection geometry were used in inkjet printing? This is a key question and I do not pretend to have all the answers. I have looked at a number of deflection geometries at least as portrayed on websites and it is clear that most designs are not optimal and some are very far from optimal. Curiously a few designs seem to be on the right track. Perhaps they saw my papers or perhaps the design was empirically optimized. With a properly designed deflection device, the ink droplets could be deflected into large angles and the entire droplet will experience the identical force. That means the droplet will not be pulled apart and spray ink. The droplet will ride along an equipotential line, the force will be perpendicular to the trajectory and the droplets will not break-up or splatter. The geometry will require less physical space and perhaps allow the print head to be closer to the target. One less power supply would be needed. I assume these would be beneficial.

In those applications where deflection is more than just binary, this device could make major improvements. The deflection is more precise and controllable.

One possible drawback is that in order to take full advantage of the improved deflection design, reduced variation on both droplet charge and droplet mass may be required. I am unaware of any other possible detrimental effect that would be associated with using the offset injection device.

Conclusions

The next logical step would be to work with an equipment manufacturer. I would take a good critical look at a current design and, working with their engineers to better understand cost, maintenance and performance considerations, use my custom software to propose a new design to optimize ink droplet deflection.

References

[1] M. **Retsky** and R. **Stein**. Testing an electron beam deflection innovation: Initial results. Jour. Vacuum Science and Tech. B 20(6): 2678-2681 Nov/Dec 2002 (http://www.elopt.com/JVSandT-2002.pdf)

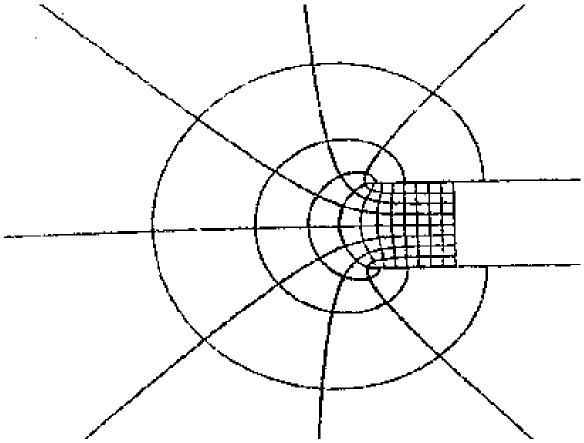

Figure 1. *The equipotentials and lines of force are shown for the case of two parallel flat conductive plates at different voltages. The fields are complex and sharply changing near the edges. Approximately one gap spacing inside the plates, the fields are much more uniform. The usual method of ray tracing in such situations is to assume the fields are negligible outside the plates and uniform inside the plates. The weakness of that approximation is apparent as can be seen. Electron optics engineers attempt to avoid aberrations from the edges by injecting their beams centrally. The idea proposed here is to inject the charged particle stream offset so as to ride somewhat along an equipotential. Originally developed for electron beams, this idea is now proposed for charged ink droplets.*

Author Biography

Michael Retsky (Ph.D. in physics - University of Chicago - 1974) has worked in electron beam related technology at Zenith Electronics (Chicago) and Hewlett-Packard (Colorado Springs). He currently owns small business Electron Optics. He also is on faculty at Harvard Medical School. He is known for dogma challenging theories concerning cancer growth and response to therapy. Michael is on the board of directors of the Colon Cancer Alliance and also at Connecticut Optics and Photonics Association.