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Inkjet Printing and the Steady State Macroscopic Mechanical Energy Balance (SSMMEB) Equation

Steven J Simske; HP Labs; 3390 E. Harmony Rd. MS 66; Fort Collins, CO 80528 USA

Abstract

The author is a co-author on a Wiley book under preparation entitled the "Handbook of Industrial Inkjet" (chief editor Werner Zapka). One area of relevant new content in this book is in surface manufacturing, which refers to the customization of a finished product – usually a manufactured good – by using printing and/or printing-like processes. Surface manufacturing is a form of additive manufacturing in which there is a template in the form of a partially finished object upon which to use as a surface for the (usually product-finishing) custom manufacturing. There are four major types of inkjetting that can be considered for a role in surface manufacturing. After describing these, we then consider their use in surface manufacturing in light of the Steady State Macroscopic Mechanical Energy Balance (SSMMEB) Equation. Some approaches to designing for variability are then discussed.

Introduction

Mass customization is an approach to product manufacturing in which each object can be customized, which means that specific design options are provided to the mass production manufacturer and these are used as finished product options. The concept of "re-distributed manufacturing" is an enabler for mass customization of partly mass-produced goods. The ability to finish goods locally (mass customization) has significant cultural advantages (better understanding of the customer), reduced shipping costs, reduced inventory costs, and economic advantages due to the "recirculation" of money generated by the manufacturing sector. Will inkjet printers (e.g. print service providers and existing inkjet manufacturers) lead the way in custom and surface manufacturing? That remains to be seen, but one thing is certain: inkjet technologies will definitely play a role. Extrusion-based surface manufacturing of polymers is already a key part of additive manufacturing, and ceramics, metals and composite materials are moving in that direction. Inkjet technologies can be used to guide the flow of materials to a surface (intelligent extrusion), and thus perform a wide range of finishing steps for a custom (or even, in some cases, a mass-produced) manufactured good. We describe the four salient inkjet technologies next.

Inkjet Technologies: TIJ

The first inkjet technology considered her is thermal inkjet (TIJ). TIJ delivers ink (or other fluids capable of nucleation) through the rapid application of heat to a plate or resistor that leads to rapid bubble nucleation in the pressure chamber, followed by droplet ejection, bubble collapse and the (usually capillary-action driven) refill of the drop ejection chamber.

The bubble nucleation is caused by rapid heating of a resistor, which heats a small (a thickness of approximately 0.1 micron thick is heated to 340 C at about 200 million degrees/second—this is usually less than 2% of the volume of the chamber) portion of the ink in the chamber. A bubble of superheated ink vapor is produced within a few (usually 3-10) µsec of the pulse being sent to the resistor. The rapid expansion of the bubble forces out the rest of the ink from the chamber exit orifice, usually within 10-20 µsec. The drop is made cohesive by the surface tension of the ink and the structure of the orifice. Once the droplet is ejected, bubble collapse and capillary force refill typically occurs within 20-40 µsec of the thermal event, depending on chamber architecture.

Momentum of the capillary force driven ink flux causes the ink meniscus to overshoot the orifice in the 40-50 µsec post-thermal event timeframe, with reasonable fluid equilibrium occurring at about 80 µsec.

The important items to take forward from the TIJ description are (a) the entire event takes 20-80 µsec, corresponding to a firing rate of up to 50 kHz; (b) the vapor bubble acts like a piston forcing ink through the nozzle, so that the same event can be used to move fluids through small tubes or "pipes"; (c) nozzle densities of up to 500 nozzles/cm can be supported, meaning the chambers can be staggered every 20 microns; and (d) a wide range of aqueous inks supporting dyes, pigments, latex and conductive elements can be moved by the thermal events.

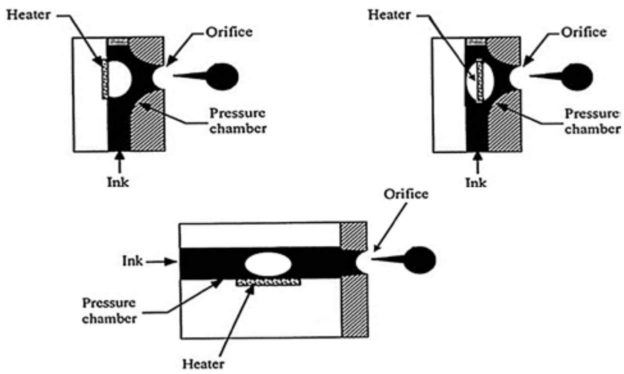

Figure 1. *Thermal Inkjet examples, modified from [2] and kindly provided by Ron Askeland.*

Three different TIJ configurations are shown in Figure 1. An important difference between these configurations is the relative location and orientation of the resistor (heater) and the orifice. Since the nucleation event creates an evanescent bubble, it can be used to direct flow in any desired configuration (flow will simply proceed where resistance to flow is lesser). As a consequence, TIJ can be used in a wide variety of surface manufacturing configurations. The heating chamber can be equipped with a 1-way valve, in one implementation, which closes during the thermal event and thus forces the flow in a single direction. Using this, TIJ can be used for more than simply printing—it can be used for extrusion and bulk flow of a low-to-middle viscosity fluid.

Inkjet Technologies: PIJ

The definition of "piezoelectric" is the generation of an electric charge in response to applied mechanical stress (or vice versa). In piezoelectric inkjetting (PIJ), an electrical pulse is applied to a piezoelectric element (usually made of PZT), which defects a diaphragm by approximately 1 micron. The structure of the PIJ chamber leads to a resonance effect, producing high fluid velocity at the nozzle location. Based on the nature of the electrical signal, several different droplet volumes can be delivered from the same chamber. Four different PIJ configurations are illustrated in Figure 2.

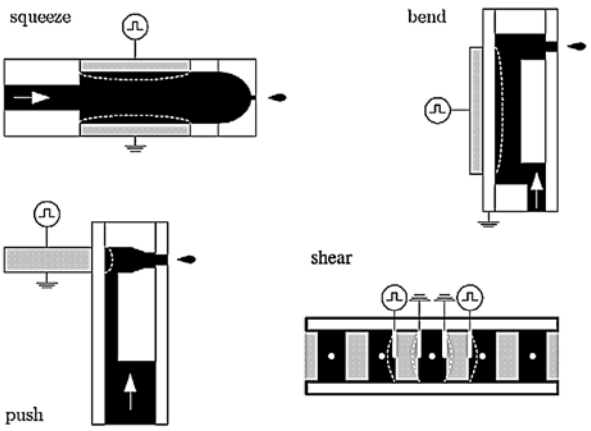

Figure 2. *Piezoelectric Inkjet examples, modified from [2] and kindly provided by Ron Askeland.*

Because of the mechanical event involved, PIJ chambers usually cannot be packaged at densities above 70 nozzles/cm. However, the PIJ chambers can support a very wide variety of aqueous, solvent, white pigmented, magnetic pigmented, and UV inks. This allows PIJ technologies to support a wide variety of substrate materials. More importantly for surface manufacturing, PIJ can be used to deliver highly viscous finishing materials like paints and lacquers. The relatively higher cost per nozzle and low nozzle density may limit PIJ's use in high-resolution manufacturing.

Inkjet Technologies: CIJ

Continuous inkjetting (CIJ) is a printing technology in which an ink stream is broken into droplets of uniform size and spacing by applying a pressure wave pattern to an orifice. As the drops move from the orifice, they are charged electrically and then deflected. Depending on the charge, the droplets in the upper diagram of Figure 3 are electrostatically deflection onto a number of different raster positions (allowing text characters to be printed readily). Unused droplets—droplets which have not been charged in the upper diagram of Figure 3, or droplets which have been charged in the lower diagram of Figure 3—are (re-)collected using a gutter mechanism. This prevents ink waste and, because the droplet formation rate is constant, simplifies the engineering design.

Because of the simple droplet formation mechanism, a wide range of viscosities, solvents and solids loads are accommodated. The droplet velocity is high, affording long throw distances of greater than 2 mm—the limiting factor being the air resistance effects. Because of the simplicity of design, the droplet frequency can be made very high. The continuous nature of the flow prevents short term decap.

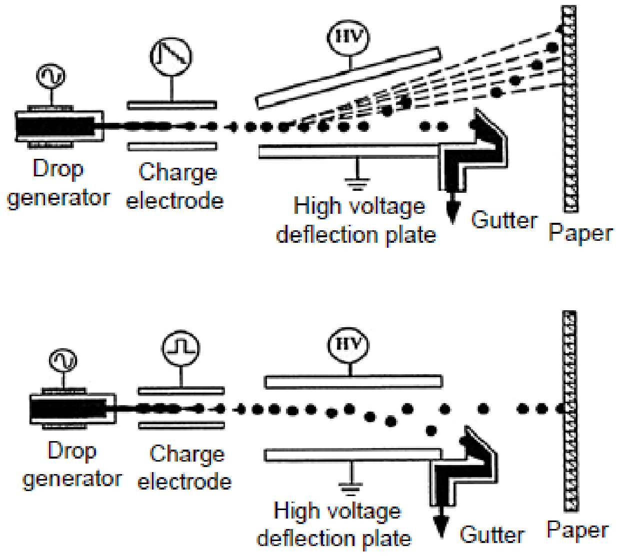

Figure 3. *Continuous Inkjet (CIJ) examples, modified from [2] and kindly provided by Ron Askeland,*

While the drop generation system is relatively simple, the CIJ ink re-circulation system is relatively complex, and nozzle wear time is reduced by the continuous droplet formation. Overall, therefore, the printhead manufacturing cost is relatively high.

Inkjet Technologies: MIJ

The fourth primary inkjet technology is mechanical inkjet (MIJ). Figure 4 shows a typical incarnation.

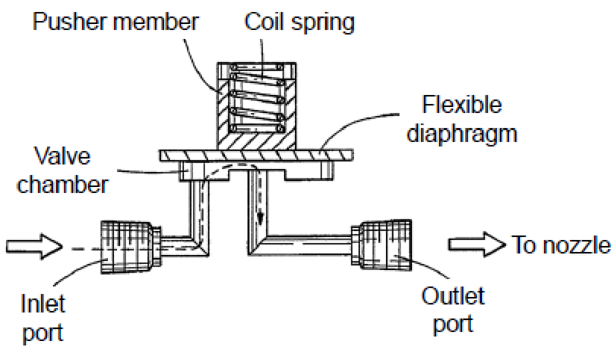

Figure 4. *Mechanical Inkjet (MIJ). Diagram kindly provided by Ron Askeland,*

With MIJ, the drop ejection process is governed by a fast-acting solenoid valve that is used to selectively control the flow of pressurized ink through the nozzle.

The SSMMEB Equation

The flow of materials through an inkjet channel (either manufactured through lithographic or 3D printing methods) and the associated energies is governed by the Steady-State Macroscopic Mechanical Energy Balance (SSMMEB) equation, which will be discussed in some detail here due to its importance in applying inkjet principles to surface manufacturing. The general form of the equation [Bird et al., 1960] has been known for some time, and is given by the following equation:

$$\Delta \frac{1}{2}\frac{\langle \bar{v}^3 \rangle}{\langle \bar{v} \rangle} + \Delta\phi + \int_{p_1}^{p_2} \frac{1}{\rho} dp + \hat{W} + \hat{E}_v = 0 \quad (1)$$

In this equation $\bar{v}$ is the velocity vector or profile, which means that for turbulent flow,

$\Delta \frac{1}{2}\frac{\langle \bar{v}^3 \rangle}{\langle \bar{v} \rangle}$ is approximated by $\Delta \frac{1}{2}\bar{v}^2$

The scalar ρ is the density, and the term $\Delta\phi$ is the potential energy (which can be positive or negative depending on the relative positioning of the ink reservoir and the ink printing nozzle.

Table 1. The SSMMEB Equation and Thermal Inkjet (TIJ) Printing Considerations

Factor in the Steady-State Macroscopic Mechanical Energy Balance equation	**Thermal Inkjet (TIJ) Considerations**
$\Delta \frac{1}{2}\frac{\langle \bar{v}^3 \rangle}{\langle \bar{v} \rangle}$	Velocity will generally be pulsatile due to the nature of TIJ nucleation and "explosion"
$\Delta\phi$	Value depends on the relative position of the reservoir and nozzle
$\int_{p_1}^{p_2} \frac{1}{\rho} dp$	Pulsatile due to the nucleation and explosive nature of chamber evacuation
$\hat{W}$	Most of the work for the pulsatile flow comes from the nucleation event
$\hat{E}_v$	Ink near nucleation event gives off heat

The integral

$$\int_{p_1}^{p_2} \frac{1}{\rho} dp$$

is, in isothermal systems, the Gibb's free energy, or $\Delta\hat{G}$, which is equal to the change in free enthalpy, or $\Delta H - T\Delta S$. The term

$$\hat{W}$$

is the mechanical work done by the fluid on its surroundings. In many industrial applications, this term may be appreciable; for example, if the fluid is used to push open a one-way gate in a pipeline. The

$$\hat{E}_v$$

term in Equation 1 is the frictional, or thermal, loss to the surroundings. This term can be further elaborated as shown in Equation 2:

$$\hat{E}_v = \Delta \frac{1}{2}\bar{v}^2 e_v \quad (2)$$

Here, the factor

$$e_v$$

is a function of Reynolds number and thus changes as the relative laminar vs. turbulent behavior of the flow changes.

Table 2. The SSMMEB Equation and Piezoelectric Inkjet (PIJ) Printing Considerations

Factor in the Steady-State Macroscopic Mechanical Energy Balance equation	**Piezoelectric Inkjet (PIJ) Considerations**
$\Delta \frac{1}{2}\frac{\langle \bar{v}^3 \rangle}{\langle \bar{v} \rangle}$	Velocity is pulsatile based on the mechanics of ink drop firing
$\Delta\phi$	Value depends on the relative position of the reservoir and nozzle
$\int_{p_1}^{p_2} \frac{1}{\rho} dp$	Pulsatile due to the use of mechanical stress (and thus pressure) to fire the nozzle
$\hat{W}$	Most of the work for the pulsatile flow comes from the mechanical stress on the chamber
$\hat{E}_v$	The inks experience a largely isothermal history throughout their passage

Factors in the Steady-State Macroscopic Mechanical Energy Balance equation and their relationship to four primary inkjetting technologies are provided in Tables 1-4. Note that different inkjet approaches will be ideal for different types of extrusion applications. For example, thermal inkjet (TIJ, Table 1) is a good technology to deploy when wishing to move fluids through tubes (pipes) since the heating elements can be associated with one-way valves and with different fluid resistances in multiple direction from the heating chamber (with the concomitant differential flow rates). Higher viscosity fluids will dampen the pulsatile nature of the TIJ events.

Table 3. The SSMMEB Equation and Continuous Inkjet (CIJ) Printing Considerations

Factor in the Steady-State Macroscopic Mechanical Energy Balance equation	**Continuous Inkjet (CIJ) Considerations**
$\Delta \frac{1}{2} \frac{\langle \bar{v}^3 \rangle}{\langle \bar{v} \rangle}$	Velocity is pulsatile but usually with a characteristic intra-droplet frequency
$\Delta \phi$	Value depends on the relative position of the reservoir and nozzle
$\int_{p_1}^{p_2} \frac{1}{\rho} dp$	Steady, pulsatile pressure waveforms
$\hat{W}$	Most of the work for the pulsatile flow comes from the ink dispensing
$\hat{E}_v$	The inks experience a largely isothermal history throughout their passage

For PIJ printing (Table 2), the mechanical event can be coordinated with (or provide the mechanical energy for) valve opening, switching, movement of gears, and other mechanical events. If the PIJ chamber is capable of multiple mechanical resonances, different mechanical events can be triggered by the different settings.

For CIJ printing (Table 3), the dot frequency and the variation in angle can be controlled independently to provide a range of ink density spanning several orders of magnitude; additional with active use of the gutter. As with PIJ, CIJ technologies do not result in thermal changes to the fluid, ensuring that heat-sensitive materials, including biological ones, are undamaged (no matter how slightly).

The fourth major inkjetting technology, mechanical inkjetting (MIJ), is also conceptually the simplest. A single switch is used to control a solenoid valve, which at low frequency allows the MIJ device to function as an extruder. The MIJ technology can be used for underlayers, especially when the extruded material is of moderate or high viscosity and/or adhesiveness. If the valve is left open, MIJ acts like a macro form of CIJ for the appropriate materials.

Given these considerations, we now look at the SSMMEB and the inkjetting technologies at a wider overall scale.

Table 4. The SSMMEB Equation and Thermal Inkjet (TIJ) Printing Considerations

Factor in the Steady-State Macroscopic Mechanical Energy Balance equation	**Mechanical Inkjet (MIJ) Considerations**
$\Delta \frac{1}{2} \frac{\langle \bar{v}^3 \rangle}{\langle \bar{v} \rangle}$	Velocity can be maintained if the MIJ valve is kept open
$\Delta \phi$	Value depends on the relative position of the reservoir and nozzle
$\int_{p_1}^{p_2} \frac{1}{\rho} dp$	Pressure drop can be made constant on a per unit length basis if the MIJ valve is kept open
$\hat{W}$	With the valve open, back pressure provides the work
$\hat{E}_v$	The inks experience a largely isothermal history throughout their passage

Discussion

The values for

$$e_v$$

are known for a number of conditions, including entrance into a channel, expansion or contraction of a channel, passing through globe valves and various angled turns, allowing it to be readily calculated along with the other factors in Equation 1. These SSMMEB factors differ based on the type of inkjet technology used. Tables 1-4 summarize the five factors as they relate to four important inkjetting technologies: TIJ, PIJ, CIJ and mechanical inkjetting, or MIJ.

The first factor is proportional to the square of the velocity of the jetted fluid. For a pulsatile jetting technology (TIJ, PIJ and CIJ), the velocity will exhibit two behaviors: a non-zero velocity when the droplet is ejected and a "zero velocity" behavior between drops. The pause between droplets can be adjusted to provide a closer approximation to isothermal behavior, or at least some cooling, as desired for the surface and the material being added to the surface. For MIJ, so long as the valve is open, a steady-state velocity profile can be achieved and maintained. This can be used to control the temperature within an optimum range for a wide range of materials, depending on reaction thermals (endothermicity, exothermicity, peak temperature, etc.) concerns of the process.

The potential energy factor depends on the relative location of the material (ink) reservoir and the nozzle(s). However, additional potential energy can be factored in at the manufacturing surface if the nozzles are positioned any appreciable distance above the surface. This type of potential energy will of course be directly converted into kinetic energy (and subsequently to heat) through the laws of conservation of energy.

The third term,

$$\int_{p_1}^{p_2} \frac{1}{\rho} dp$$

is directly affected by pressure differences in the system. TIJ systems in particular will have very pulsatile behavior for this value, since the pressure changes during droplet formation can be substantial. For PIJ printing, changes in pressure are innately part of the droplet formation. For MIJ printing, pressure changes during valve open/close are large. The severity of pressure changes can be mitigated through any of several easily-employed approaches, including one-way gates, turns in the material pipeline/pathway, or the introduction of obstructions at key locations along the pathway. The latter can affect the laminar vs. turbulent behavior of the flow.

The work done on the system and the heat absorbed or released by the material can be controlled in a vast number of ways: for example, active or passive heating or cooling; obstructions such as grates, screens or partial barriers; or the use of energy scrubbers such as turbines.

As illustrated here, the SSMMEB equation can be used to determine how best to control the extrusion velocity, temperature and inertia, allowing significant adaptability in how surface manufacturing is accomplished with inkjetting.

Conclusions

As the examples show, the repertoire of inkjetting technologies provide a wide array of options for surface manufacturing. In the case of TIJ, pulsatile temperature behavior can be used to trigger specific reactions and to differentially move fluids through tubes/pipes. Both TIJ and PIJ can provide pulsatile mechanical behavior suitable for actuating moving parts such as valves and flywheels. CIJ and MIJ technologies are capable of providing a wide range of coating thicknesses for materials with widely different viscosities, particulate profiles and volatilities.

As 3D printing and other forms of additive manufacturing help empower more custom manufacturing than at any time since before the Industrial Revolution, inkjetting technologies are certain to be a part of it. Using the SSMMEB is one way of investigating the role each of the inkjetting technologies might play in this new custom manufacturing environment.

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Author Biography

Steven Simske is an HP Fellow and A Director in HP Labs. He is the author of more than 400 publications and roughly 140 US patents. He is an IS&T Fellow and an honorary professor at the University of Nottingham. Steve has been a member of the World Economic Forum Global Agenda Councils since 2010, including Illicit Trade, Illicit Economy and the Future of Electronics. At HP, he directs teams in research on 3D printing, education, life sciences, sensing, authentication, packaging, imaging and manufacturing. His book "Meta-Algorithmics" addresses intelligent systems.

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