Optimizing Cleaning Energy in Batch and Inline Spray Systems

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Steve Stach, Austin American Technology

Mike Bixenman, Kyzen Corporation

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Abstract
The cleaning industry is constantly challenged to improve cleaning processes, staying ahead of the ever-advancing technology curve as it applies to new fields of application. Processes are commonly represented as mechanical and chemical energy, temperature and time. With increasing complexity of board and component geometry coupled to more difficult solder paste and flux formulations, cost of ownership concerns reduce the ability of temperature and time to be effective process variables. As a result, mechanical and chemical energy must make up for reduced temperatures and shorter process times.

Typical approaches to increasing mechanical and chemical effectiveness are counter productive for cost of ownership concerns and achieve only diminished returns. New approaches to mechanical energy are introduced in a way to deliver performance at the heart of the residue, rather than the tail of the delivery system. Coupled with new formulations, which are optimized for lower temperatures of operations, new levels of performance, cost modeling, and throughput are achieved simply by answering these following questions with a thoughtful perspective. What spray configuration is needed at the board level? What type of impingement pressure is needed at the board level? Which is better, high pressure or high flow? All driving towards a single question, is it possible to define a physical equation to determine impingement pressure to penetrate under densely populated components?

Introduction
The benefit of well defined, controlled precision cleaning process improves manufacturing efficiencies and increases product yields. An optimized cleaning process is one where the cleaning agent effectively removes the contaminant of the day, as well as those foreseen on your corporate technology roadmap. In addition, in an optimized process, the cleaning equipment and chemistries must also be integrated. The hardware is responsible for delivering the cleaning agent, as well as providing some mechanism for control and re-use spent solvent or rinse water after processing. After careful consideration, the net result is an environmental safe cleaning system provides quality product without contingent liabilities.

One of the most recent developments in electronics manufacturing today is the convergence of circuit board and die packaging technologies. The new developments for each technology can be combined for higher performance electronic devices. Technical issues such as low standoff and fine pitch solder bump arrays increase the difficulty of post-reflow defluxing. Ionics may be trapped underneath an active circuit and the spacing between conductors may pose a risk of electromigration. The process engineer must develop expertise in process optimization, process control and chemistries for the requirements of the package design.

Statement of Problem
The cleaning industry is constantly challenged to improve cleaning processes, staying ahead of the ever-advancing technology curve as it applies to increasingly new fields of application. Processes are commonly represented as mechanical and chemical energy, temperature and time. With increasing complexity of board and component geometry coupled to more difficult solder paste and flux formulations, cost of ownership concerns reduce the ability of temperature and time to be effective process variables. As a result, mechanical and chemical energy must make up for reduced temperatures and shorter process times. Typical approaches to increasing mechanical and chemical

effectiveness are counter productive for cost of ownership concerns and achieve only diminished returns.

Statement of Purpose

New approaches to mechanical energy deliver performance at the heart of the residue, rather than the tail of the delivery system. Coupled with new formulations, which are optimized for lower temperatures of operations, new levels of performance, cost modeling and throughput are achieved simply by answering these following questions with a thoughtful perspective. The purpose of this work is developing an equation that will allow optimal spray configuration and impingement pressure at the board level, to improve cleaning performance.

Research Questions

- What kind of equations defines surface energy at board level?
- How does this affect the fluid delivery design in a cleaning system?
- How much impingement pressure is needed at the board level?
- Which is better, high pressure or high flow?

Study Hypothesis

H_1: Understanding the dynamics of flow, pressure, and dissolution, a physical equation to determine impingement pressure to penetrate under densely populated components can be defined.

Conceptual Model / Theoretical Framework

Time and material are the metrics that manufacturing is judged by, to produce a quality product. The objective of any production team is to keep the cost low while consistently achieving product quality standards. To achieve the lowest cost requires a high production rate and an optimized process. The science of optimizing air spray cleaning performance requires an accurate model to predict performance. All cleaning systems are governed by two fundamental principles: the solubility rate of the residue in the cleaning solution and the physical energy available in the cleaning system. Equation 1 describes this relationship.

Equation 1: Process cleaning rate equation: $\mathbf{R_p} = \mathbf{R_s} + \mathbf{R_d}$

Where;
Process cleaning rate = $\mathbf{R_p}$
Static cleaning rate = $\mathbf{R_s}$
Dynamic cleaning rate = $\mathbf{R_d}$

In equation 1, $\mathbf{R_p}$, $\mathbf{R_s}$ and $\mathbf{R_d}$ are the rates of removal of contaminate per unit of time. Units will vary depending on the residues being cleaned. Rates for cleaning flux residue, rinsing wash chemistry, or drying water from a circuit assembly can be expressed as thickness or mass removed/second, volume flushed/second or mass removed/second. If solder balls or other particles were in the soil, then balls/second or particles/second would be appropriate units. When comparing rates of different cleaning processes, it may be appropriate to specify rates at the same temperature since rates are temperature dependent.

Defining "An Optimized System" - The objective of the "spray in air", batch, or inline cleaning systems is to reduce time by increasing the $\mathbf{R_d}$ component. Maximizing the physical energy delivered at the surface to be cleaned, in general, increases the $\mathbf{R_d}$. A word of caution: avoid machine selection solely based on secondary indicators such as horsepower of the pump or manifold pressure. Shakespeare once wrote, "Full of sound and fury and signifying nothing".

An optimized "spray in air" is not overpowered or oversized. An optimized cleaning system delivers the necessary chemistry and energy to clean the most difficult or sensitive areas, at a rate that will meet the process time requirement using minimal chemical, energy and floor space consumption. In this definition of an optimized "spray in air" cleaning system, it is important to note that the system should be designed to clean the toughest or most electrically sensitive areas of the parts to be manufactured. Minimum gap, largest or most complex component usually leads the way to identifying these areas.

The $\mathbf{R_s}$ + $\mathbf{R_d}$ Balance

Understanding the balance of $\mathbf{R_s}$ and $\mathbf{R_d}$ is key in predicting and optimizing process performance at each step of the washing, rinsing, and drying process. Suppose for a minute that we washed our clothes by throwing them in a bucket of soapy water overnight. The water would dissolve the salts and sugars thoroughly and rapidly because of the high solubility rate ($\mathbf{R_s}$). The oils and greases would disappear slower and perhaps incompletely due to marginal solubility and low dissolution rates. Earth's persistent gravity (9.8M/sec) would be the only energy available to the static bucket cleaner to remove insoluble dirt and other adherent soils and some of it might drop off, but most would remain behind. Understanding the nature of the soil and the chemical and physical needs for removing it, allow us to select the bucket for a silk blouse with a coke stain or the heavy-duty cycle on our washing machine for kids play clothes.

Rates of Rinsing and Drying

Equation 1 also applies in the rinsing or drying cycles. In the rinsing cycle, we are removing wash fluid with the soils dissolved or suspended. In the dryer, we are removing relatively clean rinse water by evaporation or displacement. Displacement of water by air impingement is preferred in automated systems, as evaporative dryers require 100 to 1000 times more time than displacement dryers and can leave residues or etch metallic surfaces.

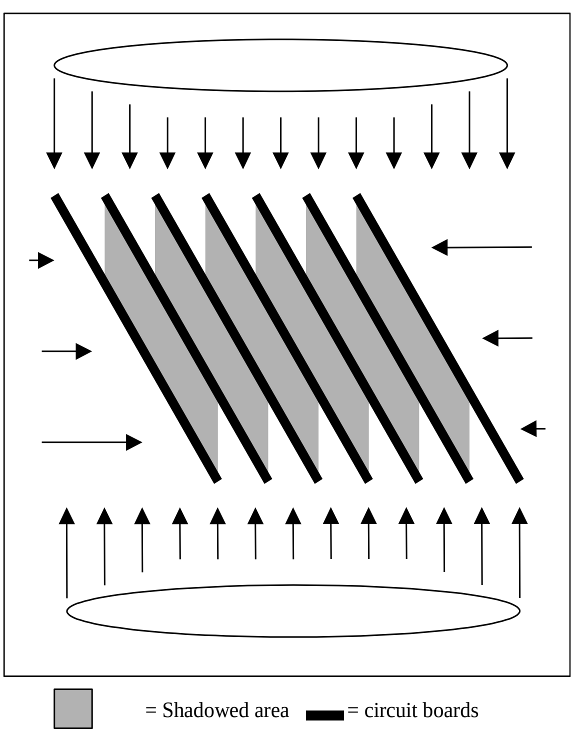
Normally, $\mathbf{R_s}$ or $\mathbf{R_d}$ dominates a given cleaning process step. Inline "air spray" cleaners and planarized batch cleaners are examples of cleaning processes dominated by high **R_d's**. Dip tanks, "spray under immersion", "dishwasher style" batch "air spray" cleaners and vapor degreasers are examples of cleaning processes dominated by high $\mathbf{R_s}$. Typical dominance of spray in air cleaner designs are shown in Table 1:

System Design	**Wash**		**Rinse**		**Dry**	
	%R_s	**%R_d**	**%R_s**	**%R_d**	**%R_s**	**%R_d**
Static Immersion	100%	0%	100 %	0%	100 %	0%
Dish Washer	70%	30%	70%	30%	50%	50%
Planarized Batch	30%	70%	40%	60%	20%	80%
Inline Air Spray	20%	80%	20%	80%	2%	98%

Table 1: Comparison of R_s and R_d for typical cleaning processes

It is important to note the differences between "dish washer style" batch systems, and inline "air spray" systems. These differences primarily arise due to "shadowing" of parts and certain board surfaces in 3 dimensional racking baskets (see figure 1). The inline and planarized batch process has a higher % $\mathbf{R_d}$ because all board surfaces are delivered tangent to the direction of spray and are therefore much less subject to shadowing.

Figure 1: Shadowing in Dishwasher Style Cleaners



Types of Surface Energy

Surface energy is the energy available at the cleaning surface to do work. Remember that R_d in equation 1 is the rate work as contributed by the cleaner. This rate is exclusively driven by surface energy. Energy is measured in ergs for mass, and velocities are measured in grams and centimeters.

For conversion convenience, 1 Joule = 10^7 ergs = 0.239 calories = .73 ft·lbs = 2.78X10^{-7}kW·hrs. Force is measured in dynes and is the force exerted by one gram accelerated by earth's gravity for one cm. Translated from English to metric, 1 lb/in^2 = 68948 dynes /cm^2.

In air spray systems, the work of cleaning requires energy to displace a fluid across a distance to create the force sufficient to achieve the rate of cleaning, rinsing and required drying. Fluid flow is created by spray impingement pressure, gravity drainage, and capillary action. Table 2 shows impingement pressure can be the most significant force available to do work.

Table 2: Sources of surface energy in aqueous systems

Source of Surface Energy	**Range of Energy Available**	**Governing Equation**
Capillary action	0-2"wc (0-1.0 psi)	$P_c = 2 \cdot \gamma \ / \ R$
Gravity Flow	0-1"wc (0-0.5 psi)	$P_g = \rho \cdot g \cdot h$
Impingement Pressure	0-275"wc (0-10 psi)	$Pi = ½(rv^2)$

wc = water column

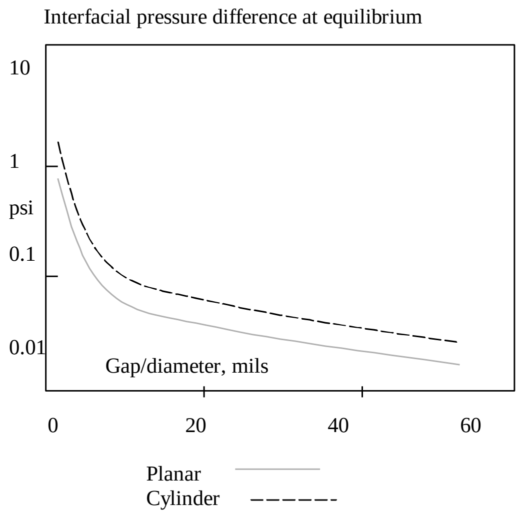
Surface Tension & Capillary Action

Surface tension can be thought of as a balloon of sorts surrounding the cleaning fluid. If it is thin and weak, the cleaning fluid can easily move in an out of tight spaces. If surface tension is strong, it will resist flow into tight spaces.

Capillary attraction or repulsion is a force resultant of adhesion, cohesion, and surface tension of cleaning fluid in contact with the parts to be cleaned. The resultant interfacial pressure is referred to as the capillary force.

Graph 1 shows the interfacial pressure difference for water in a planar and cylindrical glass interface as a function of the gap. The pressure can be calculated by equation 2 or 3.

Graph 1



Equation 2: Interfacial pressure differential (for planes)[1]
$\Delta p = 2\gamma / R$

Equation 3: Interfacial pressure differential (for tubes)[1]
$\Delta p = \gamma / R$

Where γ = surface tension; **R** = radius meniscus

Capillary forces can work for you and against you. They can facilitate the initial wetting of tight spaces. They also will inhibit the rinsing and drying steps by resisting displacement forces if insufficient. Graph #1 indicates it would take an air jet impingement force of greater the 1-psi to displace water trapped in spaces less than 1 mil.

Calculating Surface Energy

Cleaning fluids can have both potential and kinetic energy. The potential energy can be expressed as shown in equation 4.

Equation 4: Potential energy of one unit volume of fluid at rest[2] = $E_p = \rho \cdot g \cdot h$

Where;
ρ = density of fluid
g = acceleration due to gravity = 9800 cm/sec/sec
h = height of fluid (cm)

The kinetic energy contribution can be calculated as shown in equation 5.

Equation 5: Kinetic energy of one unit volume of cleaning fluid in motion[2] = $E_k = \frac{1}{2} \rho v^2$
Where ρ = density of fluid
v = velocity of jet

Solving equations 4 and 5 for water systems reveals two important points. First, the potential energy is small as compared to the kinetic impingement. Second, the E_k is driven by the v^2 term, which can be maximized by nozzle and pump design. This is the basis of the earlier warning not to purchase equipment solely based on horsepower. If the jets or nozzles are not optimized for the pump and stand off distance, excessive splash or spray atomization can retard the energy delivered by reducing impingement velocity. A well-designed spray manifold will deliver energy of the pump efficiently over distance with minimal losses of this type.

The efficiency of a manifold can be measured by dividing the impingement pressure at maximum working distance by the manifold pressure. An average spray manifold efficiency of 5-10% is typical of today's "spray on air" cleaning systems. New high efficiency spray manifold designs can achieve 25% and increase surface cleaning energy by a factor of $1/2V^2$. This can boost surface energy 2X to 10X in the cleaning, rinsing and drying steps.

Bernoulli Equation Modifications

Daniel Bernoulli suggested in the 1700's that the total pressure of a fluid in a pipe is equal to the static pressure plus the kinetic energy and the potential energy. This relationship is well known and published in every physics textbook[2].

Equation 6: $P_e + \frac{1}{2} \rho v^2 + \rho g h$ = total pressure = Constant

Where;
P_e = internal pressure energy
ρ = density of fluid
v = velocity of fluid
g = acceleration due to gravity = 9800 cm/sec/sec
h = height of fluid (cm)

We can apply the Bernoulli equation to an unrestrained jet striking the cleaning surface by removing the internal pressure energy factor P_e and adding the surface energy effect of capillary action. This gives a modified Bernoulli equation, which can be used to predict the cleaning surface energy.

Equation 7: Bernoulli Equation modified for surface cleaning energy:
$\frac{1}{2} \rho v^2 + \rho g h + 2\gamma / R$ = total force at tightest gap

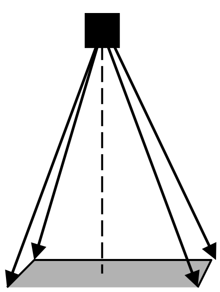
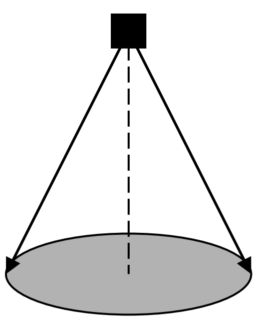
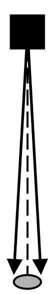
R is the contact radius of the meniscus in the gap. It will change with gap size from surface to surface. **R** will have a negative value if meniscus is convex instead of concave.

The implication of a negative force at any step is that the washing, rinsing, or drying fluids will not penetrate and the overall cleaning rate would be zero in that gap.

Spray System Nozzle Design

Nozzles are used in air spray systems to create jets that carry the energy to the surface of the part to be cleaned, rinsed, or dried. The design and layout of the nozzles becomes important if the cleaning system is to be truly optimized. Equation 5 gives the kinetic energy of the jet at the surface of the board. This equation has both mass and velocity components. Conical and fan nozzles spread the spray to cover larger areas at the expense of reducing the mass per unit and velocity of the jet. Coherent jets hold together longer and delivers more energy to a smaller area requiring more nozzles and a higher over all flow rate.

Table 3: Comparison of Fluid Jets

Spray Type	Typical pressure @ 2",50psi man. /Pressure loss/in	Indicated use
Fan/Delta 	2 psi / ~50% drop/inch	Wide coverage, overlapping high impingement for close work distance
Conical 	0.4 psi / ~75% drop/inch	Widest coverage area, lowest kinetic energy, flooding applications
Coherent 	10 psi / ~25% drop/inch	Smallest coverage, highest energy density over longest distance

All jets will break-up and slow down over distance in air. Coherent jets hold together longer giving the maximum energy transfer per unit area. Overlapping jets can be an effective strategy for increasing surface energy density as long as the splash at the surface does not dampen the impact force.

Empirical measurements of coherent and fan jet nozzles are listed in table 4 and show a coherent jet delivers 5-10 X more impingement pressure than fan nozzles at the same manifold pressure depending on distance[3].

Table 4: Impingement/flow data of coherent jet vs. fan

Manifold Pressure	Flow: (gpm)	Impingement psi @			Coverage width @	
0.075"Coherent Jet		1"	2"	4"	1.5"	4.0"
30 psig	0.69	15	10	6.5	0.6	0.7
40 psig	0.82	17	12	8	0.6	0.7
50 psig	0.89	19	13	9.5	0.6	0.8
60 psig	0.97	20	15	11	0.6	0.8
F40-1.0 Fan Nozzle						
30 psig	0.89	3.2	1.6	0.2	1.5	3.25
40 psig	1.06	4.4	1.8	0.3	1.7	3.60
50 psig	1.20	6.0	2.3	0.5	1.7	4.0
60 psig	1.30	7.2	2.5	0.5	1.8	4.0

The cleaning rates in inline and planar racked batch cleaners can be significantly improved if designed with coherent jets or a combination of fan-jets and coherent jets in the wash and rinse sections. As previously mention, coherent jets in the dryers offers considerable improvement in effectiveness.

Inline Cleaning, Jets and Timing

The timing and sequence of events in a cleaning process is critical. Each section or step in the process requires careful thought and understanding. The pre-wash should thoroughly wet the parts with the wash solution chemistry and provide sufficient flow and contact time to bring the assembly to wash temperature. This facilitates the full static-cleaning rate, R_s, in the cleaning chemistry. Residues are softened and dissolved in the soak zone between the pre-wash and the wash segment.

In the wash zone, the part should see several high impingement scourings, punctuated by brief soak periods. This optimizes the static rate by maintaining fresh cleaning fluid and optimizes the dynamic rate by focusing the maximum physical energy at the part surfaces.

In the chemical isolation section there should be ample impingement force in the first air jet manifold to strip the wash chemistry from the assembly so that it can be returned to the wash tank. A second jet air and/or water manifold should thoroughly remove any remaining residue to drain. In the power rinse section, a series of high-pressure nozzles removes and dilutes the remaining ions using de-ionized water. A low flow/pressure final pure rinse of DI water and one more soak to ring out the very last ions, and boom, there ready for a high-speed impingement displacement dry.

Dishwashers are Different

"Dishwasher" style cleaners are different from planar type batch and inline cleaners. Dishwasher style cleaners are most efficient when designed for maximum flow, not impingement, as potential energy and capillary forces must be relied upon for cleaning surface energy in the shadowed areas. Using too high pressure tends to atomize the spray reducing jet velocity much faster over distance and increases the splash interference with other jets.

Optimized jets in "dishwasher" style batch cleaners provide large cohesive droplets from relatively large, low-pressure coherent jets. These large droplets adhere to the assemblies rather than bounce or splash like their high pressure cousins and provide a more consistent and through cleaning in shadowed areas.

Energy in "dishwasher" style cleaners can be optimized by fixturing the assemblies in a way such that the chance of shadowing is minimized.

Solubility's Contribution

The traditional approach "dissolve it" is age old, tried and true. Although it is often augmented with various forms of physical assistance such as heating, blasting and scrubbing, dissolving the residue remains fundamental to most cleaning applications. The Rate of solubility, Rs, in any given cleaning system is dependent on the dissolution rate (**Dr**); the effect temperature of the residue being dissolved (**Tc**); and the concentration of the residue in the solvent (**Cc**).

Table 2: Effect of temperature on various residue types

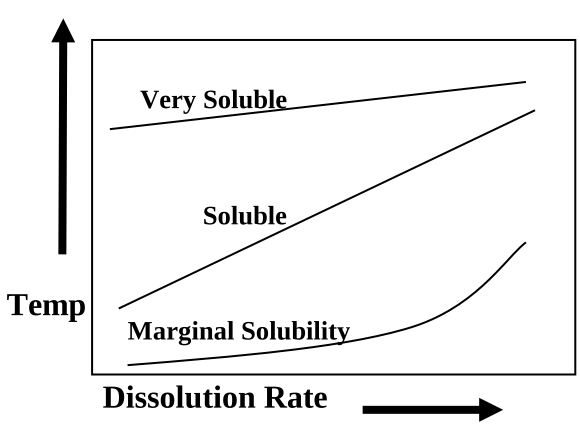


Table 2 represents three distinct residue types. The top line indicates residues like finger salts that are very soluble at room temperature. The only challenge here is to assure all surfaces are wetted and rinsed properly. The middle line represents a residue, which is much more soluble in heated wash solution. Heating here would shorten cleaning time and improve cleaning efficiency. The third line represents a marginally soluble residue. It requires heat and/or physical energy to assist in the removal process.

Equation 8: Rs = **Dr** x **Tc** x **Cc**

The **Dr**, **Tc,** and **Cc** can easily be determined experimentally by weighing the residue dissolved in a fixed period of time. The temperature coefficient, **Tc** is the ratio of the rate at a higher temperature, divided by the rate at a lower temperature. Similarly, concentration coefficient, **Cc** can be determined by dividing rate of dissolution in contaminated solvent by the rate of dissolution in pure solvent.

Contamination Effect

Remember what you learned in chemistry class, "like dissolves like". This is generally true for most solvent wash solutions, but not all cleaning solutions or cleaning applications. It is true that the more rosin you dissolve in terpene, the better it works, up to a point. It eventually gets too thick or difficult to rinse. This adage holds when a solvent chemically similarly to the residue is used to remove a residue.

This would not hold true with a saponification cleaning system or other cleaning systems where one or more of the cleaning agents are depleted over time. This also would not be the case if marginally soluble salts or weak organic acids were being used in an aqueous system. Contamination of the wash bath in these cases slows the cleaning process by shifting the chemical equilibrium of the wash solution. The ionization potential (Pka) and corresponding relationship to dissolved and un-dissolved ionic concentrations in equilibrium is shown in equation 9[4].

Equation 9: Pka=[anion][cation]/[residue]

The complexities of this arise when residues contain multiple constituents. Some have high solubility, and some may have low solubility. Dissolving the soluble constituents may leave behind the insoluble constituents as a physical residue requiring significant time and/or physical energy to remove.

Conclusion

The science of optimizing air spray cleaning performance requires an accurate model to predict performance. All cleaning systems are governed by two fundamental principles: the solubility rate of the residue in the cleaning solution and the physical energy available in the cleaning system. Maximizing the physical energy delivered to the surface to be cleaned increases the dynamic cleaning rate. An optimized cleaning system delivers the necessary chemistry and energy to clean the most difficult or sensitive areas, at a rate that will meet the process time requirement using minimal chemical, energy and floor space consumption. Understanding the static cleaning rate plus the dynamic cleaning rate balance is key in predicting and optimizing process performance at each step of the washing, rinsing, and drying process.

Surface energy is the energy available at the cleaning surface to do work. The surface energy can be calculated at any point using a modified Bernoulli Equation. In air spray systems, the work of cleaning requires energy to displace a fluid across a distance to create the force sufficient to achieve the rate of cleaning, rinsing, and required drying. If surface tension is thin and non-restrictive, the cleaning fluid can easily move in and out of tight place. Capillary forces can work for and against the process since they facilitate initial wetting but inhibit rinsing and drying steps. Understanding the fluids potential and kinetic energy allows for a nozzle and pump configuration that maximizes surface energy. The efficiency of the manifold can increase surface cleaning by as much as 25%.

The design and layout of the nozzles is an important step toward optimization. Conical and fan nozzles spread the spray to cover larger areas. Coherent jets hold together longer giving maximum energy transfer per unit area. Overlapping jets can be an effective strategy for increasing surface energy density.

The rate of chemical dissolution can be augmented with various forms of physical assistance such as heating, impingement and time. Contamination loading can slow the cleaning process by shifting the chemical equilibrium of the wash solution. Contaminant complexities arise when residues contain multiple constituents.

Follow On Research

Phase II of this research proves or nullifies the research hypothesis. The study design will focus on the solubility rate of the cleaning solution at static conditions. Once the cleaning solution rate is known, how will it be improved applying physical energy to the board surface? The designed experiment will test the effect of energy applied to the board surface. Logic tells us that a known dissolution rate and a known surface energy configuration will allow for an equation that will allow an engineer to calculate cleaning time and distance.

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Authors

Steve Stach, President of Austin American Technology, which is a market leader of aqueous bath and aqueous inline cleaning equipment. E-mail address: sstach@aat-corp.com

Mike Bixenman, Chief Technology Officer of Kyzen Corporation, which is leading provider of engineered cleaning materials for electronic assembly manufacturing environments. E-mail address: mike_bix@kyzen.com