Chapter 18

Applications of Supersonic Gas-Liquid Cleaning Systems for Removal of Surface Contaminants

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1 INTRODUCTION

In recent years, many new concerns have been raised about the use of solvents for precision cleaning in industrial applications. Concerns about ozone depletion, global warming, and air pollution have led to new regulations and mandates for the reduction of chlorinated solvents, hydrochlorofluorocarbons (HCFCs), trichloroethane and other ozone-depleting solvents, and their eventual phase out [1–3]. The search for alternate cleaning methods to replace these solvents has led to the consideration of various alternate cleaning systems [4–6 and references therein]. This chapter is focused on the applications of supersonic gas-liquid cleaning for removing surface contaminants. The cleaning method was reviewed recently [7]. The purpose of this chapter is to update the information from the previous review.

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2 SURFACE CONTAMINATION AND CLEANLINESS LEVELS

Surface contamination can be in many forms and may be present in a variety of states on the surface [8]. The most common categories of surface contaminants include:

- Particles
- Organic contaminants which may be present as hydrocarbon films or organic residues such as oil droplets, grease, resin additives, waxes, etc.
- Molecular contamination that can be organic or inorganic
- Metallic contaminants present as discrete particles
- Ionic contaminants including cations and anions.
- Microbiological contaminants such as bacteria, fungi, biofilms, etc.

Common contamination sources can include machining oils and greases, hydraulic and cleaning fluids, adhesives, waxes, human contamination, and particulates, as well as from manufacturing process operations. In addition, a whole host of other chemical contaminants from a variety of sources may soil a surface.

Cleaning specifications are typically based on the amount of specific or characteristic contaminant remaining on the surface after it has been cleaned. Product cleanliness levels in precision technology applications are specified for particles by size (in the micrometer (μm) size range) and number of particles, as well as for hydrocarbon contamination represented by nonvolatile residue (NVR) in mass per unit area for surfaces or mass per unit volume for liquids [9–11]. The surface cleanliness levels are based on contamination levels established in industry standard IEST-STD-CC1246E for particles from Level 5 to Level 1000 and for NVR from Level R1E-5 (10 ng/0.1 m^2) to Level R25 (25 mg/0.1 m^2) [11]. A new international standard defines the cleanliness of surfaces in cleanrooms with respect to the presence of particles [12]. It applies to all solid surfaces in cleanrooms and associated controlled environments such as walls, ceilings, floors, working environment, tools, equipment, and devices. The surface particle cleanliness classification is limited to particles between 0.05 μm and 500 μm. A new standard ISO 14644-13 has been published that gives guidelines for cleaning of surfaces in cleanrooms to achieve defined levels of cleanliness in terms of particles and chemical classifications [13].

Many of the products and manufacturing processes are also sensitive to, or they can even be destroyed by, airborne molecular contaminants (AMCs) that are present due to external, process or otherwise generated sources, making it essential to monitor and control AMCs [14]. An AMC is a chemical contaminant in the form of vapors or aerosols that can be organic or inorganic, and it includes everything from acids and bases to organometallic compounds and dopants [15,16]. A new standard ISO 14644-10, “Cleanrooms and associated controlled environments – Part 10: Classification of surface cleanliness by chemical concentration” [17] is now available as an international standard that defines the classification system for cleanliness of surfaces in cleanrooms with respect to the presence of chemical compounds or elements (including molecules, ions, atoms, and particles).

In many commercial applications, the precision cleanliness level is defined as an organic contaminant level of less than 10 μg of contaminant per cm^2, although for many applications the requirement is set at 1 $\mu g/cm^2$ [11]. This cleanliness level is either very desirable, or it is required by the functional use of parts such as metal devices, electronic assemblies, optical and laser components, precision mechanical parts, and computer parts.

3 BACKGROUND TO SUPERSONIC GAS-LIQUID CLEANING

Commercial spray cleaning systems are well established for cleaning various types of parts and surfaces. These systems employ high pressures for cleaning, use large quantities of fluids, and are unsuitable for precision cleaning. If solvents are also used for cleaning, they pose a significant waste disposal problem, even if the solvents are not regulated and are approved for use. As an example, the Kennedy Space Center (KSC) of the National Aeronautics and Space Administration (NASA) in Merritt Island, Florida was processing approximately 2 50 000 small and large components (such as valves, pipes, regulators, flexible hose lines and compressed gas cylinders) through the cleaning facility each year, consuming as much as 27 000 kg of chlorofluorocarbon (CFC) solvent (CFC 113) for cleaning and verification purposes [18–20]. Historically, at KSC precision cleaning to remove surface contamination (particulate and nonvolatile residue) was to flow large quantities of water with detergents at high temperature or to flow large volumes of CFC solvents over the components, which tended to be a significant enviornmental problem. The strict cleanliness requirements were derived from liquid oxygen (LOX) system compatibility, since particles and hydrocarbon greases and oils can easily ignite in the presence of LOX. Subsequently, the level of cleanliness was verified according to NASA specification [10] that requires quantitative measurements of particle contamination (number of particles per unit area) and NVR as mass per unit area for space components designed for LOX service and for other fluid systems where high levels of cleanliness are required. This was performed by flushing the defined surface area (0.1 m^2) with a CFC solvent. For particle contamination, the solvent was poured through a filter and the particles were counted using an optical microscope. The NVR analysis was performed gravimetrically by evaporating the collected solvent and weighing the remaining solid residue.

An effective method was needed at KSC to replace this system of cleaning and verification employing such large volumes of solvents. Other cleaning methods like high pressure water jets, ultrasonic cleaning, and flushing with approved solvents had several disadvantages. Although ultrasonic cleaning is very effective in removing contaminants, the component must be immersed in the cleaning fluid. The large size of most components cleaned at KSC made this impractical. Water jet cleaning disadvantages included high volumes of water consumption and the relatively high pressures required for effective contaminant removal. In spite of their excellent solvency potential, cleaning and flushing with even approved solvents does not solve the issue of consumption of large volumes of used solvent which have to be processed, and the tendency for solvent flushing to leave behind insoluble contaminants.

To overcome these disadvantages, the supersonic gas-liquid cleaning (SS-GLC) concept was developed by accelerating liquid droplets to supersonic velocities (>Mach 3) by using a converging-diverging nozzle and medium pressure (~2 MPa) compressed inert gas or air [21–24]. SS-GLC provided advantages over alternate cleaning methods. Benefits over water jet cleaning included lower operating pressures, less water consumption, and greater surface impingement capability. Benefits over solvent flushing included the elimination of solvent consumption and the removal of insoluble particles by impingement. Using a spraying nozzle meant that large surfaces that could not be immersed in an ultrsonic bath could be cleaned. SS-GLC also provided several advantages over other pressurized cleaning methods. The system did not abrade the surface of the parts being cleaned, and it required much lower levels of pressure while using very little water. These features enabled the system to clean a wide variety of items from printed circuit boards to painted surfaces, as well as to remove adhesives, flux, and even fingerprints [24].

In medical applications, removal of solid contaminants from and cleansing of exposed in vivo tissue is necessary during surgical procedures [25]. In addition, such cleansing is necessary in preparation for treatment for dental conditions such as gingivitis, caused by the long-term effects of plaque deposits. Organic matter tends to bond to tissue much more strongly than nonorganic matter, and is generally more difficult to remove than nonorganic matter such as fibers, dust, and sand particles. Cleaning with a liquid such as water is often ineffective in removing the particles that are smaller than the thickness of the stagnant laminar boundary layer (flow velocity is zero at the surface) which is formed on the tissue surface [26]. The particles located in the boundary layer have a sufficiently high drag force that cannot be overcome by a liquid stream even with a very high overall velocity.

3.1 Principle of Supersonic Gas-Liquid Cleaning

SS-GLC is effective in removing particle and nonparticle (hydrocarbon film) contaminants. The system mixes gas and liquid from separate pressurized sources: the liquid is suspended as fine droplets in the gas stream. The nozzle has a converging-diverging geometry. Assuming homogeneous and adiabatic uniform velocity with thermal equilibriun (rapid heat transfer) between the gas and the liquid, the compressibility of the gas can accelerate the atomized liquid particles to supersonic velocities [22,23]. Recent work has shown that the assumption of rapid heat transfer between the gas and liquid phases is incorrect; rather, the assumption of no heat transfer between the phases may be more appropriate in describing nozzle flow because liquid droplets have been observed in the jet exiting the nozzle [27,28]. At the same time, a stagnant liquid boundary layer cannot form on the surface because of the small quantity of liquid used for cleaning. The gas-liquid mixture is ejected at supersonic speeds from one or more nozzles at the end of a hand-held wand assembly. At these speeds, the liquid droplets suspended in the gas have the kinetic energy to forcibly dislodge the solid contaminants from the surface, dispersing them into a minimal waste stream. Even small particles that, due to their size, may be trapped in a liquid boundary layer can be removed.

The dominant mechanism for hydrocarbon residue removal is due to emulsification upon liquid droplet impact with the target surface [22,29]. The supersonic nozzle tends to emulsify hydrocarbon contaminants, so that the concentration exceeds the contaminant solubility limit in the liquid. The emulsification process is dependent on the size and concentration of the liquid droplets present in the mixture, as well as nozzle design and injection arrangement [29–33].

3.2 Description of the Method and Equipment

The main uses of SS-GLC cleaning are for precision cleaning and for medical applications.

3.2.1 Precision Cleaning Systems

Several gas-liquid jet cleaning devices have been developed to improve cleaning of a variety of surfaces and systems using one or more of these devices are available commercially [34–55]. These systems provide a liquid stream with a reduced boundary layer thickness employing liquid and gas nozzle assemblies; a high velocity aerosol of at least partially frozen particles; and pulsed jets of liquid sprayed onto a metal surface to remove small particles.

For precision cleaning applications, SS-GLC operates by flowing high-pressure air or nitrogen through a throttling valve to the nozzle. Water is injected into the gas flow stream through an inlet orifice upstream of the converging/diverging section of the nozzle. The nozzle design is based on an area ratio (ratio of exit area to the throat area) of 5.44 which gives a Mach number of 3.14 corresponding to a velocity of approximately 1067 m/s (Fig. 18.1) [22]. At this point the rate of change in Mach number with area ratio begins to decrease significantly. More recent work has shown that the measured velocity, 630 m/s, and the computed velocity, 670 m/s, of the gas-liquid mixture are in good agreement, but approximately two-thirds of the expected velocity based on the original design calculations [56]. Two different nozzle designs have been developed and are commonly employed in cleaning applications. In the conventional converging-diverging nozzle, the two-phase jet discharging from the

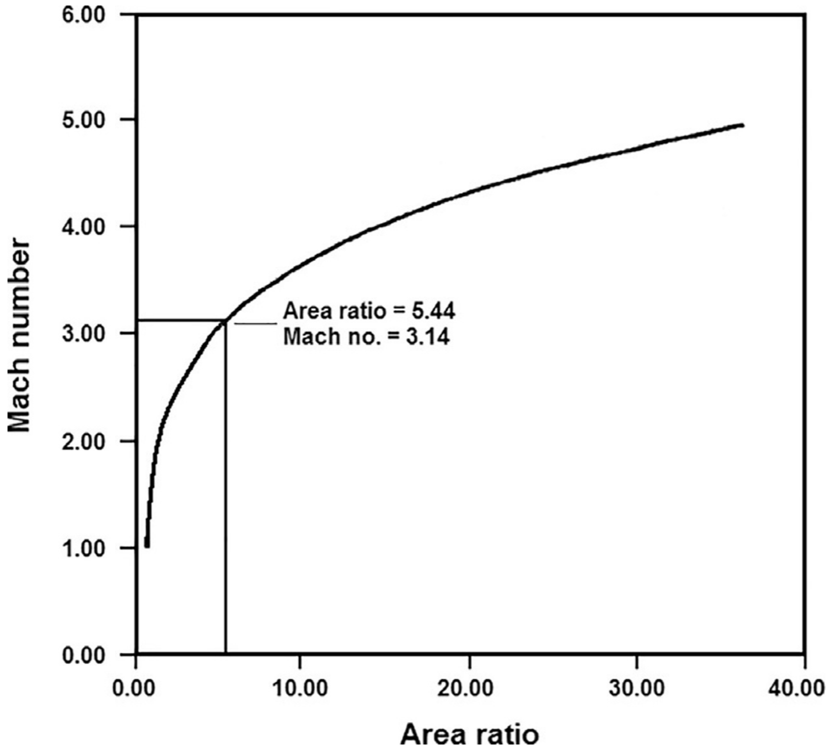

FIGURE 18.1 Mach number vs area ratio for the KSC SS-GLC converging-diverging nozzle [22].

conventional nozzle diverges, thus creating a wider jet with smaller concentration of liquid droplets at the cleaning surface. By contrast, the jet in the annular nozzle converges at the exit and reaches its greatest concentration a short distance downstream of the nozzle outlet (Fig. 18.2) [31–33,58]. The jet diameter and intensity are narrower and the concentration of droplets at the target surface is higher than the conventional nozzle at the same pressure and flow rate. The conventional nozzle can cover a larger surface area than the annular nozzle. Supersonic exit velocities can be achieved without an inordinately large exit cone in the nozzle.

The mixed gas-liquid flow then enters the converging-diverging nozzle where it is accelerated to supersonic speeds. The supersonic gas-liquid stream is directed onto the surface of the components that require cleaning or cleanliness verification (Fig. 18.3).

The velocity imparted to the water by the gas flow gives it sufficient momentum at impact to remove contaminants on the surface of the component being cleaned or verified while simultaneously dissolving the contaminant in the water, which can be captured for cleanliness verification. The flow parameters for the gas-liquid nozzle can be set so virtually any gas and liquid can be

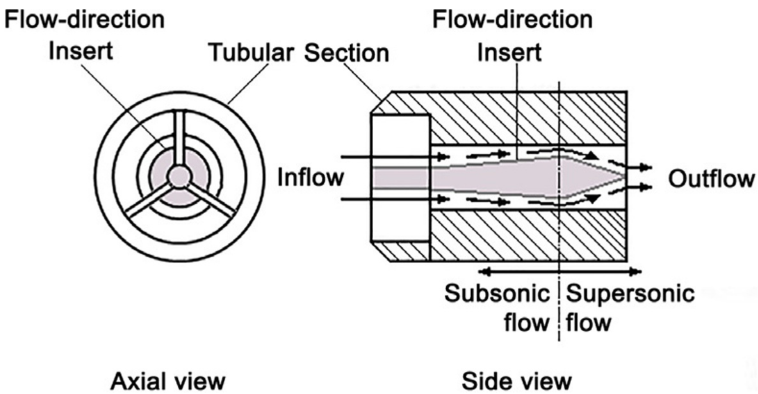

FIGURE 18.2 Converging-diverging nozzle with flow-directing annular insert [31–33,57].

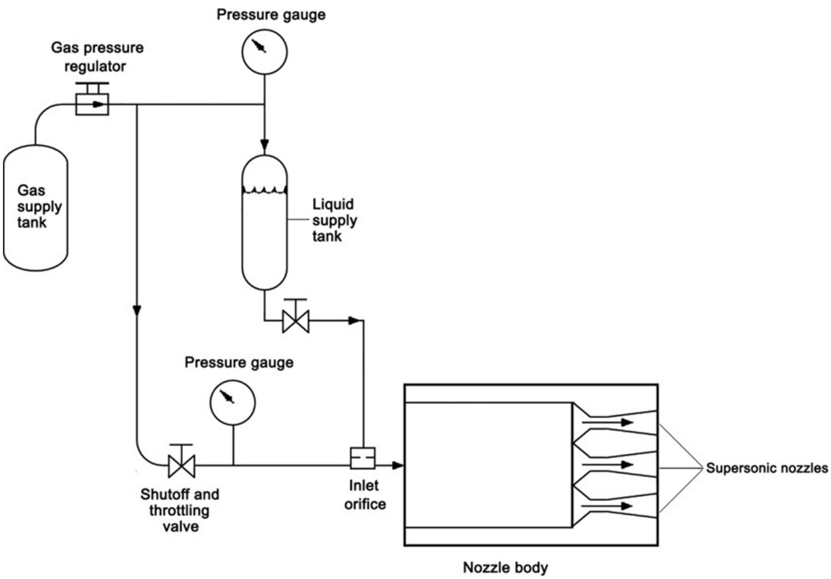

FIGURE 18.3 Schematic of the basic supersonic gas-liquid cleaning system for precision cleaning applications [22,23].

used for a desired flow and mixing ratio. In addition, the size and number of nozzles are adjustable. This adjustability makes it possible to create sizes ranging from small handheld cleaning nozzles to very large multiple-nozzle configurations. For cleanliness verification the cleaning fluid is replaced with water which can be collected for analysis after spraying the surface of the cleaned part (Fig. 18.4). The small volume of cleaning fluid results in reduced solvent usage and the resultant cost of hazardous waste disposal.

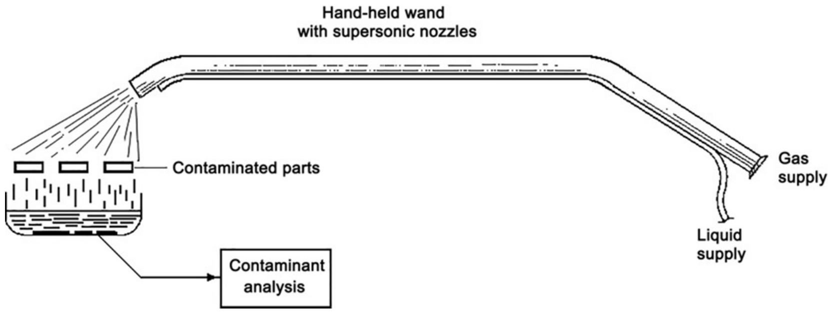

FIGURE 18.4 Supersonic gas-liquid cleaning system arranged for precision cleaning and cleanliness verification [23].

A commercial SS-GLC system based on this design has been developed.[1] The system accommodates the use of distilled or deionized water and the use of compressed breathing air or nitrogen. All wetted parts are fabricated from stainless steel or Teflon™. Cleaning and drying functions are controlled from a single trigger. Since the environmentally-friendly system requires less than 100 mL of water per minute, there is very little liquid left after cleaning that must be handled as contaminated waste.

The system is non-abrasive due to the low mass energy of the atomized water, approximately 0.13×10^{-6} kg-m/s per 1 μm size water drop, as compared with other spray cleaning methods (see Table 18.1).

With a nozzle that can be oriented in any direction, the system is adjustable to allow all sides of a part to be cleaned without reorientation. Designed for operator safety and comfort, the system requires minimal training for operation and can be easily moved on built-in casters, despite its weight (~200 kg). When operating the SS-GLC adequate hearing protection is required during operation due to the supersonic velocities. Maintenance is minimal with only a few moving parts.

3.2.2 Medical Cleaning Systems

Many of the dermal abrasion and cleansing systems use relatively high liquid flow rates which reduces the cleansing and scouring effect due to the virtually stagnant boundary layer that develops over the surface to be cleaned. High velocity can also cause damage to the surface. Other devices have low flow rate, low pressure nozzles for mixing fluids, but they employ Venturi tube injection to atomize the liquid, which cannot achieve supersonic velocity in the mixture. In general, these devices provide only a small improvement over nonpulsed spray cleaning systems.

1. This system is no longer offered as a standard stock item from the vendor, although custom units can be built on customer request [59].

TABLE 18.1 Typical Parameters of Different Particle Removal Techniques [60]

Cleaning method	Impacting particle size, mm	Impacting particle density, kg/m^3	Impacting particle mass, kg	Impacting particle velocity, m/s	Momentum transferred per impacting particle, kg-m/s (10^{-6})
Dry Ice Pellet Blasting	3.18 dia × 6.35 long	1562	7.84×10^{-5}	~335	27 652
CO_2 Particles	< 1	1562	8.16×10^{-7}	46	37.33
	0.5	1562	8.16×10^{-7}	305	248.87
CO_2 Snow	1.48	780	1.31×10^{-6}	~0.3	0.41
Water Ice (small particles)	70×10^{-3}	930	1.32×10^{-9}	335	0.45
Water Ice (large particles)	1.02 dia × 6.35 long	930	1.9×10^{-5}	162	3071
SS-GLC	1×10^{-3}	1000	1.18×10^{-10}	1067	0.13
	8×10^{-3}	1000	6.01×10^{-8}	1067	64.84

The principles of SS-GLC have been applied to develop devices for multiple tissue cleansing and dermal abrasion applications [57,61,62] that overcome the limitations of other methods. The SS-GLC devices use very small amounts of the cleansing liquid to form a mist of droplets suspended in a high velocity gas. The small amount of liquid suspended as a mist prevents the formation of a liquid boundary layer which could trap small particles. The gas-liquid mixture is accelerated to supersonic velocity and is delivered to the tissue surface, mass or cavity to be abraded, thereby very effectively scouring and cleansing the surface.

The SS-GLC system developed for medical applications employs a converging-diverging gas nozzle and a liquid discharge nozzle arranged concentrically within the gas discharge nozzle. The gas nozzle configuration is operated such that the inlet gas pressure is at least twice the outlet gas pressure. This pressure drop causes a shockwave in the gas and, depending on the gas

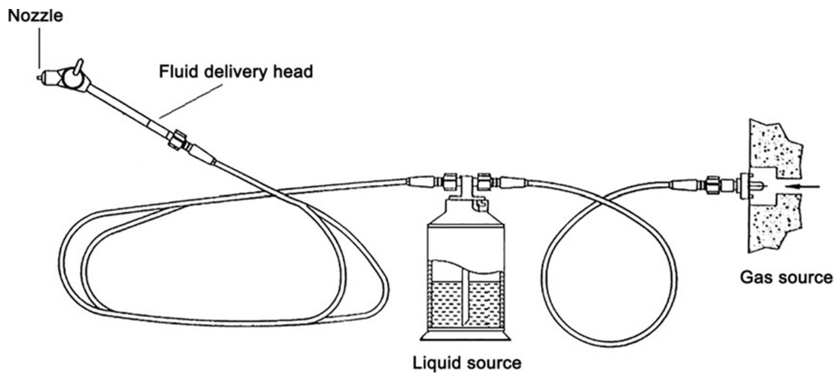

FIGURE 18.5 Schematic of the cleaning system for medical applications [57,61,62].

pressure, accelerates it to velocities ranging from subsonic to supersonic. At the same time, the liquid flow downstream of the gas discharge nozzle is atomized and forms a mist of liquid droplets (5–100 μm) suspended in the flow of discharged high velocity gas (Fig. 18.5) [57,61,62]. Gas (air, oxygen, carbon dioxide, and nitrogen) is supplied from the pressurized gas source at a pressure of 0.28–1 MPa and liquid is supplied from the pressurized liquid source at a pressure in the range 0 to 0.034 MPa. The mist jet delivery nozzle arrangement includes at least two gas discharge nozzles or at least two liquid discharge nozzles. A suction conduit is included in the mist jet delivery nozzle arrangement which provides for removal of waste liquid and abraded tissue particles. The device is designed to be used while being held in one hand.

A system based on this technology is commercially available for different applications. The JetOx™ system (Fig. 18.6) is used for wound cleansing and debridement (debridement is the surgical excision of dead, devitalized, or contaminated tissue and removal of foreign matter from a wound [65]) [63,64,66–70]. For this application, the system employs medical grade oxygen and a sterile cleaning liquid. Saline solution (0.9% sodium chloride) is most commonly employed, although other solutions have been used successfully [71–76]. The spray is precisely calibrated to treat only the affected areas. A unique shield is attached to the delivery nozzle to prevent contamination.

The JetPeel™ system is employed for dermal applications, including transdermal drug delivery [77–79]. It contains a control unit and a unique disposable handpiece that includes the delivery nozzles. The fine, single-nozzle handpiece (Fig. 18.7a) is suitable for noninvasive mesotherapy, wrinkle, and acne treatments, while the triple nozzle handpiece (Fig. 18.7b) is used for most other skin treatments. The system is lightweight and ergonomic and requires only minimal dexterity from the operator. The skin peeling depth can be precisely controlled by controlling the gas pressure and the number of passes, making it possible to individually treat different areas of skin simultaneously without collateral

FIGURE 18.6 The JetOx™ wound cleansing and debridement system [63,64]. *(Courtesy of Tav-Tech Ltd., Yehud, Israel).*

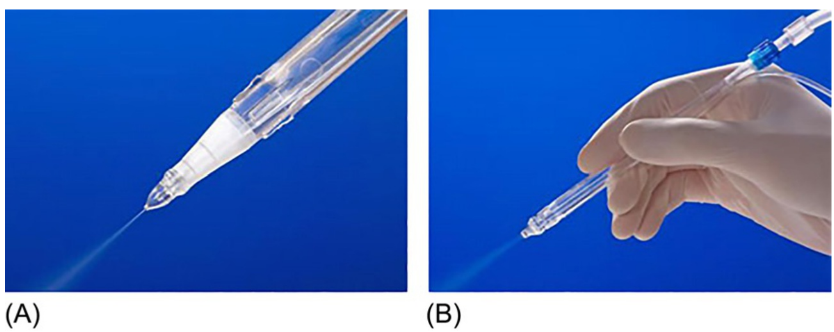

FIGURE 18.7 Handpieces for aesthetic application used with the JetPeel™ system. (a) Single-nozzle handpiece. (b) Triple-nozzle handpiece [79]. *(Courtesy of TavTech Ltd., Yehud, Israel).*

damage. JetPeel is capable of removing the epidermis layer of the skin, thereby increasing tissue oxygenation which contributes to accelerated wound healing [80].

3.3 Application Examples

Examples of applications in precision cleaning and in medical care are discussed in the following sections.

3.3.1 *Validation of Precision Cleaning Performance*

Validation of the cleaning performance of the system developed at KSC was performed [53], which required a correlation between the NVR remaining on the surface after cleaning and the total organic carbon (TOC) reading of the water sample collected after cleaning. Stainless steel witness plates with an area of ~0.09 m^2 were contaminated with a known quantity (11.1 to 111 mg/m^2) of fluorinated greases (such as Krytox®- DuPont, or Tribolube® from Aerospace Lubricants Inc.) and other common lubricants used at KSC, and then impinged with the SS-GLC system between two and eight minutes each. The TOC measurements were found to be linearly correlated with the known initial contaminant level (Fig. 18.8) and with the remaining NVR after cleaning (Fig. 18.9). The results also indicated that the nozzle emulsifies the hydrocarbon contaminants well enough to not require another cleaning step. Similar linear correlations were observed in extensive testing with other contaminants and mixtures of contaminants deposited on valve bodies and witness plates from 0.05 to 0.75 m^2 [18–21,81]. SS-GLC was shown to be a consistent technique for cleanliness verification of spaceflight hardware at KSC. The data collected also suggested that the system cleans the components more completely than the previous method using a CFC solvent (CFC-113).

A similar investigation was carried out to test the effectiveness of the KSC SS-GLC system for cleaning surfaces [59]. The samples consisted of ~0.1 m^2 304 stainless steel plates contaminated with a known quantity (7 to 18 mg) of dust and drilling lubricant, oils and hydrocarbon and fluorinated greases. The contaminated area on each plate was cleaned by impinging for two minutes with

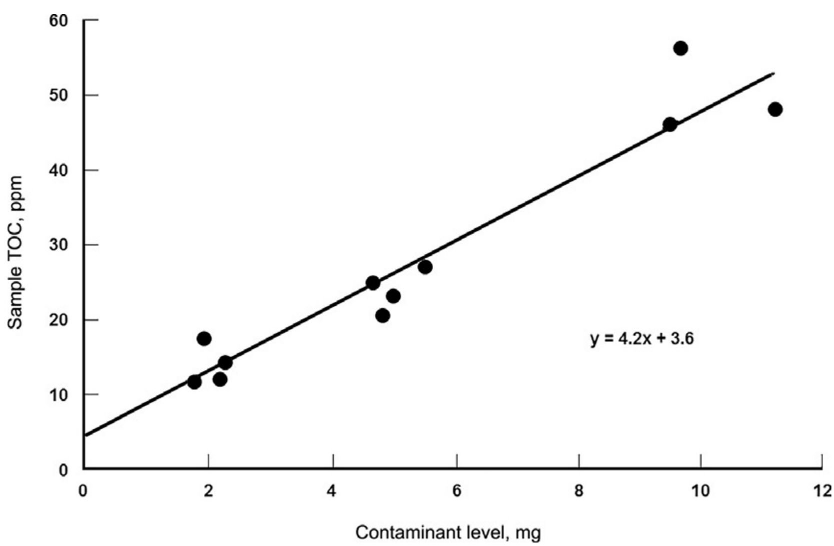

FIGURE 18.8 TOC vs the initial contaminant level of the stainless steel plates [22].

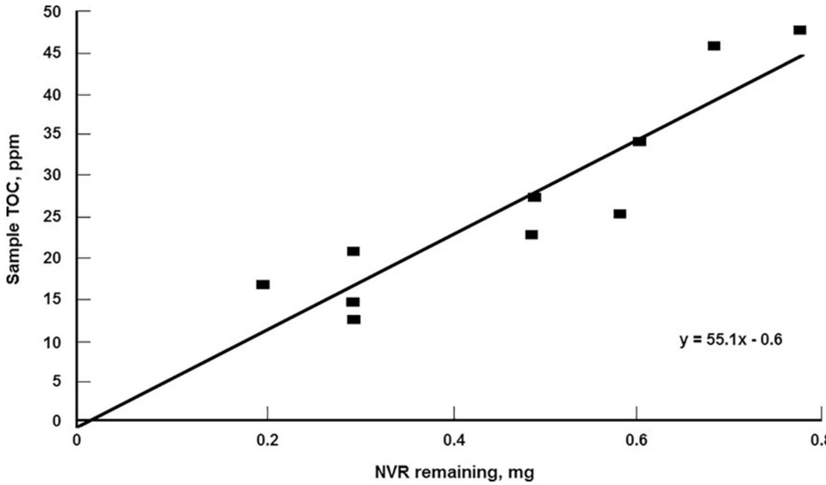

FIGURE 18.9 Linear correlation between TOC and NVR remaining after cleaning [22].

the SS-GLC system. SS-GLC tends to emulsify hydrocarbon contamination, so that it exceeds the contaminant solubility limit in water and flows off the surface. The cleanliness verification method measured the TOC in water samples collected from cleaning. Eleven of 20 plates were completely cleaned with no residue measured in the TOC samples. The TOC samples from the other 9 plates measured residue of 0.1 mg or less. The results indicate that the contaminants could be removed with greater than 96% efficiency with the SS-GLC system.

Parametric studies have been conducted with a 1.25 cm long converging-diverging nozzle in the SS-GLC system [27]. The pressure upstream of the nozzle was either 2.2 MPa or 2.89 MPa with water flow rates of 0.052 liters/min and 0.056 liters/min, respectively. The mean velocity remains nearly constant up to an axial distance of 50 mm. Increasing the air tank pressure increases the mean velocity of the flow at the exit of the nozzle from ~620 m/s to 630 m/s. The optimum tank pressure was around 2 MPa. The best working distance was found to be between 30 and 80 millimeters.

The SS-GLC technology has been adapted for cleaning and verifying the cleanliness of the interior surfaces of hollow items, such as small compressed gas cylinders (K-bottles), tanks, and long pipes and tubes (over 15 cm long) [82]. For K-bottle cleaning, the system employs a rotating spray head with 3 nozzles with only a diverging section for supplying a gas-liquid cleaning mixture to the surface of the parts at supersonic velocity. The diverging nozzle is much smaller than a full converging-diverging nozzle and can fit through the narrow opening (~1.8 cm) of the bottle, although there is a 20% loss in fluid momentum compared with the converging-diverging nozzle. One nozzle is aimed straight down the bottle, while the other nozzles are oriented at 30 and 210 degrees from the bottle axis. The orientation of the 3 nozzles covers all surfaces of the bottle. The spray head is both rotatable and translatable along its longitudinal axis. No moving parts are exposed to the interior surfaces of the items to be cleaned, thereby reducing the risk of contamination. The system can also be employed for cleanliness verification by simply replacing the cleaning liquid with plain water, and collecting and analyzing the waste water after it has been sprayed onto the item. For large pipes the full converging-diverging nozzle can be employed, so cleaning is more efficient. In this case, a pipe crawler is used to transport the rotating nozzle head through the pipe while pulling a gas-liquid supply hose.

The performance of the SS-GLC impingement system developed at KSC has been investigated in terms of the rate of contaminant removal [31–33]. Polished stainless steel substrates were contaminated with grease (8–11.5 mg/m^2) and cleaned using both the conventional converging-diverging nozzle and the annular nozzle. The rate of contaminant removal is inversely proportional to the interfacial tension between the substrate and the contaminant, which, in turn, is inversely proportional to temperature. Thus, the rate of contaminant removal by emulsification should be enhanced by increasing temperature, as was observed. A 15° jet approach angle gave the highest rate of residue removal, consistent with the theoretical consideration that the shearing force is most effective in breaking the cohesive bonds between adjacent contaminant molecules. The contaminant removal rate declined sharply with increasing distance from the cleaning surface due to reduction in droplet concentration and increased viscous drag. As expected, the cleaning performance of the annular nozzle was significantly better than that of the conventional converging-diverging nozzle under the same operating conditions. For the conventional converging-diverging nozzle, the highest removal rate was achieved at a distance of 5 cm from the surface, suggesting that the supersonic jet flow may converge at that distance. Based on these results, optimum performance of the system can be realized by using the annular nozzle with an approach angle of 15 degrees to the cleaning surface at a distance of 2 cm from the surface with as high a mixture temperature as possible without evaporating the water. The cleaning effectiveness of the system could also be increased by the addition of detergents with the lowest dynamic surface tension. Such detergents have been shown to enhance the effectiveness of spray cleaning for soil removal [83].

3.3.2 *Particle Removal*

A new system has been developed for cleaning wafers using a novel two-fluid jet nozzle which is capable of removing sub-μm particles [84]. The novel converging-diverging nozzle is capable of accelerating the liquid droplets to high velocity by a gas at relatively low supply pressure. Fig. 18.10 shows the liquid droplets accelerated by the two-fluid nozzle reaches sonic velocity at a gas supply pressure of about 3 kgf/cm^2 (line A), whereas a conventional low-pressure nozzle requires the gas supply pressure to be 10 kgf/cm^2 or above to accelerate the liquid droplets to sonic velocity (line B).

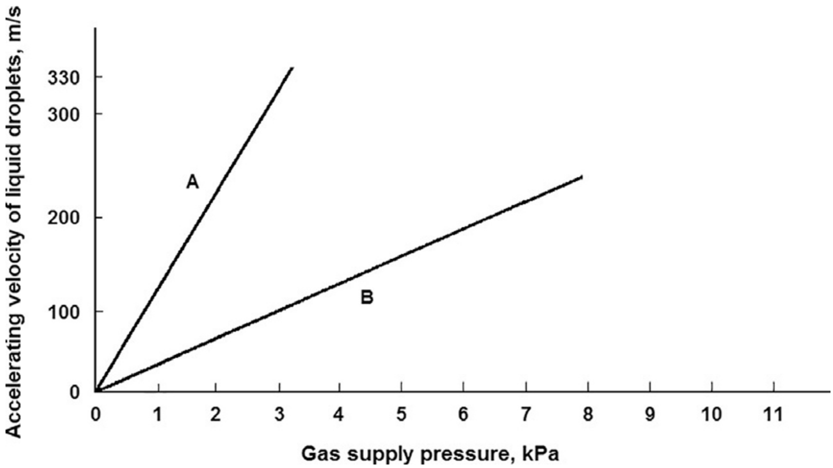

FIGURE 18.10 Graph showing the relation between the velocity of the liquid drops and the supply pressure of the gas for different jet nozzles. A. Two-fluid nozzle. B. Conventional low-pressure nozzle [84].

In semiconductor manufacturing, the maximum gas pressure used is about 7 kgf/cm^2, which is sufficient to achieve supersonic velocity of the jet exiting the two-fluid nozzle. With a conventional nozzle, the jet reaches only subsonic exit velocity. The effectiveness of this new nozzle design in cleaning wafers, represented by the contaminant removal ratio, is compared with conventional low-pressure and high-pressure jetting nozzles for similar operating conditions (Fig. 18.11). The contaminant removal ratio is defined as the ratio of the number of particles removed to the number of particles remaining on the surface. Clearly, cleaning with the new jet nozzle can remove particles smaller than 0.1 μm (curve A) as compared with the other nozzles. Although the low-pressure jet nozzle (curve B) is more effective than the high-pressure jet nozzle (curve C), it is unable to remove 0.1 μm particles.

3.3.3 Industrial Cleaning

A new nozzle design has been developed that uses a liquid to prevent clogging of powder particles in a jet spray cleaning system for industrial cleaning applications [56]. The powder is added to the gas-liquid mixture to enhance cleaning of automobiles, building surfaces, dishes, bottles, and utensils in food and beverage preparation, and other such applications. The powder tends to accumulate in passages of the nozzle where the rate of flow is low, thereby reducing the cleaning efficiency of the nozzle. Water-soluble powders also tend to absorb moisture and adhere to the walls and clog protrusions and stepped portions of the nozzle. The new design employs water as the clogging prevention liquid which is injected into a section of the pressurized gas flow between the powder

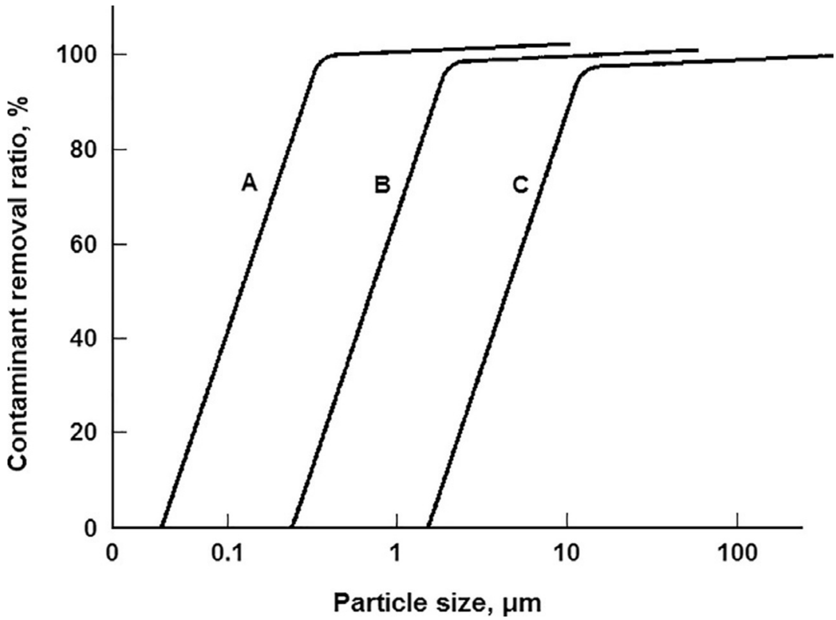

FIGURE 18.11 Plot showing the relation between contaminant removal ratio and particle size with different jet cleaning nozzles. A. New two-fluid nozzle. B. A conventional low-pressure nozzle. C. A conventional high-pressure nozzle [84].

injection section and the cleaning nozzle. The amount of clogging prevention liquid is smaller than the liquid supplied to the nozzle and is continued to be injected for a given duration after powder injection has stopped. An experiment was conducted to remove graffiti on a concrete wall by using sodium bicarbonate particles as a powder material in a high velocity gas-liquid mixture (1000 liters/min of air at a pressure of 0.39 MPa, 10 liters/min of water at 13 MPa supplied to the cleaning nozzle). Water was used as the clogging prevention liquid. No accumulation or clogging of the powder was observed in the passages of the cleaning nozzle. The powder was discharged from the nozzle as solid particles and effectively cleaned the concrete surface.

3.3.4 Heat Exchanger Tubing

The SS-GLC technology has been applied to replace mechanical and chemical cleaning and de-scaling methods currently used by various industries [85,86]. A cleaning system has been developed that consists of a spray head containing supersonic converging-diverging nozzles using a source of liquid gas, together with a novel, proprietary pumping system that permits pumping liquid nitrogen, liquid air, or supercritical carbon dioxide to pressures in the range of 138 to 417 MPa. The size and number of nozzles can be varied so the system can be built in configurations ranging from small hand-held spray heads to large multiple nozzle cleaners. The system also can be used to verify if a part has been adequately cleaned. Pilot trials on heat exchanger tubing components have shown several benefits:

- Superior cleaning in a much shorter period of time.
- Lower energy and labor requirements for cleaning and de-scaling operations.
- Significant reductions in waste volumes by not using water, acidic or basic solutions, organic solvents, or nonvolatile solid abrasives as components in the cleaning process.
- Improved energy efficiency in post-cleaning heat exchanger operations.

The cleaning system has the flexibility and adaptability for use in existing plants using heat exchangers of various designs and operational configurations. In addition to heat exchanger applications, the system has been adapted for other applications including: cleaning of coated or contaminated surfaces; air and sea infrastructure applications; mining, natural gas and oil exploration; and other potential uses.

3.3.5 Other Applications

SS-GLC system can be applied for precision cleaning in the aerospace, automotive, circuit boards, electronics, machinery, metals, plastics, and optics industries. Additional applications include contamination removal in the nuclear, agriculture, food, pharmaceutical, and chemical industries. Commercial applications range from flux removal from printed circuit boards to scouring building exteriors; removal of algae and other organic matter from boat hulls; cleaning dead-ended components; mildew and stain removal; paint removal; removal of salt contamination and surface preparation prior to painting; removal of oil stains and grease spots; and spot cooling [87].

3.3.6 Applications in Medical Care

In an early dermal application, 50 adult volunteers suffering from sun-damaged skin, facial rhytids, skin pigmentation, and post-acne facial scarring were treated with the JetPeel system [88]. The overall duration of the treatment ranged from 5 to 70 minutes. The results were judged to be aesthetically good to excellent by the patients and the medical staff, with a high degree of patient satisfaction. The technology was found to be particularly efficient in treating perioral regions due to its ability to achieve different depths of penetration of the skin. The application is more time consuming than dermal abrasion or chemical peeling, but the postreatment healing was found to be smoother and quicker which could be attributed to tissue oxygenation with the JetPeel system. One precaution recommended was to avoid the eyelids.

In another study, a group of 54 patients were treated by the JetPeel method for skin rejuvenation from scar treatment (surgical, post-traumatic injury, acne), as well as damage from pigmentation and stretch marks [89]. Six treatments of 5 to 15 minutes were performed. The depth of skin abrasion was a function of time of exposure and the distance of the nozzle from the surface. The results were very satisfactory and the rapid healing led to high patient acceptance of the procedure. Increased absorption and efficiency may be achieved by adding other treatment substances, such as vitamins and homeopathic drugs, to the saline jet stream.

In a Japanese study, the JetOx™-ND system was used to effectively treat wounds from infected abrasions, incised or crushed wounds before suturing, and wounds at graft donor sites [90]. Cleaning and debridement was performed with a saline solution and oxygen. No local anesthesia was used. The small volume of cleaning solution (100 mL) required was sufficient for treating a wound 5 cm wide and 1 cm deep and the drainage and foreign matter could be collected easily with gauze and swab. The shield prevented splashing of the cleaning solution. The author reported that the pain caused by the treatment was tolerable without local anesthesia. No cases of post-suturing infection were found. The system was considered to be effective in improving wound care in surgery and emergency situations for cleaning and debridement of wide and deep wounds.

The JetOx system was successfully used for cleansing and debridement as part of negative pressure wound therapy for adult patients over a period of 3 years with injuries of different etiologies and evolutions resulting in acute, chronic and complex wounds [91]. The deep chronic wounds represent a very high cost for health systems. Faster healing resulted in enhanced comfort and cost reduction for the patient during the healing process.

Mechanical debridement of chronic wounds may be complicated and very painful despite the use of suitable analgesics. A study was conducted to evaluate the efficacy and safety after a one-year experience with JetOx-HDC system promoting removal of fibrin, without damaging granulation tissues [92]. Ten patients with chronic leg ulcers were subjected to an average of 3 sessions with the JetOx-HDC system followed by local application of an EMLA (Eutectic Mixture of Local Anesthetics). The results showed a remarkable improvement of wound status. The treatment was found to be less painful and the patients did not need local or general anesthesia. The JetOx-HDC system is considered part of a global therapeutic strategy.

As noted earlier, the JetOx-ND system can be used with other nonsaline solutions. In one study, Ringer's lactate solution (a solution containing sodium chloride, potassium chloride, calcium chloride, and sodium lactate in distilled water) [65]) was employed to successfully clean and debride venous leg ulcers (3–50 cm^2) in a group of 55 adult patients [93]. Other solutions that have been developed and used successfully for cleansing and debridement include superoxidized water solutions (oxidized water (99.98%) with reactive species of chlorine and oxygen) and an antimicrobial solution containing dichlorine monoxide (Cl_2O) [71–76].

A pilot study was conducted to evaluate the epithelialization rates of chronic, uninfected diabetic foot ulcers in 40 adult patients treated topically with a neutral pH super-oxidized water solution [73,74]. Treatment was conducted with 25 mL of the super-oxidized solution using the JetOx system (O_2 pressure 1–1.3 kPa at 1.5 mL/min). The results showed remarkable rates of epithelialization of 0.5 mm to 0.7 mm per day with total wound closure observed between 27 and 43 days. In a control group treated with saline solution, wound closure required between 45 and 75 days.

A study of young patients involved treating 64 children with various partial and full-thickness burn injuries [94]. Debridement with the JetOx system was conducted under general anesthesia at entry, followed by moistening of the wound with a super-oxidized water solution. In general, the patients tolerated the daily cleansing and debridement without much pain. The length of hospital stay was shorter, resulting in significant cost savings.

A recent study was designed and conducted to demonstrate the effectiveness of the JetOx system in second-degree burns [95]. Twenty two patients, ranging in age from 14 months to 61 years, with burn wounds received treatment using the JetOx system with a saline solution. The hydrodebridement treatment was highly effective in removing wound debris and foreign materials with minimal to no pain reported by all patients. Rapid formation of granulation tissue demonstrated the ability of hydrodebridement to stimulate wound healing.

The JetPeel system has been used for transdermal delivery of drugs by jet nebulization [79]. In a recent application [96], anesthetic lidocaine and botulinum toxin A (BTX-A) could be safely delivered together by JetPeel to treat primary palmar, plantar and axillary hyperhidrosis, resulting in lower procedure-related pain, improved sweating and higher patient satisfaction, as compared with lidocaine delivered by JetPeel followed by standard BTX-A injection therapy. By delivering lidocaine and BTX-A together, the quantity of BTX-A could be reduced, further supporting the use of the transdermal drug delivery by jet nebulization over standard injection therapy for treatment of primary hyperhidrosis.

4 ADVANTAGES AND DISADVANTAGES OF SUPERSONIC GAS-LIQUID CLEANING

The advantages of SS-GLC for precision cleaning and for medical applications are given in the sections below.

4.1 Precision Cleaning

4.1.1 Advantages

- Uses very little cleaning liquid (< 100 mL/min)
- Reduced hazardous waste volume disposal and associated disposal costs
- Can be used for cleaning and for cleanliness verification

- Does not abrade the surface
- Adaptable design for cleaning large surfaces and parts with complex geometries
- Portable
- Few moving parts
- Operator-friendly system
- Minimal training required for operation

4.1.2 Disadvantages

- Requires tailoring for specific contaminants and applications when used as a cleanliness verification tool

4.2 Medical Applications

4.2.1 Advantages

- Uses very little cleaning liquid (< 2 mL/min)
- Versatile system that can use many different cleaning liquids
- Effective in removing very small solid contaminants that could be trapped in a surface boundary layer
- Enables noninvasive transdermal delivery of liquids (nutrient supplements, vitamins, and antiaging solutions)
- Generates minimal waste with reduced associated disposal costs
- Simple rapid setup for use
- Operator-friendly, single handed, safe operation
- Short learning curve
- Minimal training required for operation
- Precision application to desired areas for cleansing with minimal collateral damage
- Minimal pain and rapid post-treatment healing
- Portable

4.2.2 Disadvantages

- More time consuming than traditional debridement and dermal abrasion treatments

5 SUMMARY

Supersonic gas-liquid cleaning (SS-GLC) is based on accelerating the cleaning liquid, suspended as droplets in a gas stream, to supersonic velocities through a converging-diverging nozzle. The gas-liquid mixture has the kinetic energy to very effectively remove surface contaminants. SS-GLC uses very low volumes of aqueous liquids. This semi-aqueous cleaning method has been developed for various precision cleaning and medical applications, and is a viable alternative to solvent cleaning in many applications. It can also be used for cleanliness verification. SS-GLC has been successfully employed for particle removal, cleanliness performance validation, dermal applications, and wound debridement.

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