ABSTRACT

EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF WATERJET CLEANING PROCESS

by
Ping Meng

This doctoral dissertation is concerned with the development of water based cleaning technology required by industry which may substitute the traditional approach based upon the use of various chemical cleansers.

The experimental study involves the waterjet removal of various coatings (rust, oil and epoxy based paints, etc.). Cleaning was carried out under a wide range of operational and geometrical conditions (standoff distance, travel speed, water pressure, diameters of sapphire nozzle and focusing tube, nozzle body type). A new designed spiral nozzle body was tested in this work. The use of surfactant was also investigated. Microscope and SEM surface were used to evaluate the degree of coating removal. The effect of various operation conditions on water consumption and cleaning rate are determined. Two new process characteristics, critical cleaning and damage standoff distances, which determine the admissible range of process variables, are first introduced in this study.

The theoretical study pioneers an analytical description of waterjet cleaning. Simple equations relating the cleaning width of stationary and moving jets, which can be used to determine the optimal cleaning standoff distance, were constructed. These

relations show that the maximal cleaning rate and consequently minimal water consumption can be attained at a position of 0.55-0.7 of the critical cleaning standoff distance. Experimental data substantiate the results of the theoretical study.

The acquired results of the theoretical and experimental studies identify the practical range of process variables which assure complete paint removal from glass or metal surface without inducing any damage to the substrate. The spiral nozzle body was shown to provide the optimal cleaning performance. The principal result of this study, however, is a demonstration of the feasibility and effectiveness of using a high-velocity and low-volume waterjet as the single cleaning agent, and a "cleanser-free" technology. Also methods of development are outlined. Another major finding is the demonstration of the feasibility of using a conventional analytical description of turbulent liquid jets for the simulation of the behavior of a high speed stream of water droplets, which constitute the jets used in this study.

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by
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This dissertation is dedicated to
my beloved family

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LIST OF SYMBOLS

A, B	intermediate parameters
C	empirical coefficient of jet spreading
f	impact pressure
k	coefficient of the water system
$\dot{m}$	water droplet flow rate at any point inside the jet
$\dot{m}_0$	water droplet flow rate of the jet at nozzle exit
$\dot{m}_m$	$\dot{m}$ value at the jet center line
n	an empirical constant
P	water pressure from the intensifier or pump
r	distance of the point of consideration from the jet center l
r_0	radius of the nozzle
R	jet radius across the section of the jet
S	strength parameter of material or adhesive strength
S_a	adhesive strength between coating and substrate
S_c	strength of coating
t	jet duration
U_0	waterjet velocity at the nozzle exit
V	jet travel speed
w	cleaning width
w_c	cleaning width at the critical standoff distance

LIST OF SYMBOLS
(Continued)

w_m maximum cleaning width

x standoff distance

x_c critical standoff distance

x_m optimal standoff distance

y y- coordinate

z z- coordinate

ρ_w density of water

ρ_s density of coating material

α an gross coefficient of other system parameters

β mass removal of coating material per droplet

ξ dimensionless parameter defined by $\xi = \frac{r}{R}$

η coating mass loss per unit area

δ diameter of water droplet

ψ acoustic speed in water

1, 2 first and second process of cleaning

CHAPTER 1

INTRODUCTION

Removal of various contaminates, deposits and coating materials from the surface of parts or manufacturing equipment is a basic industrial technology. The shortcomings of conventional cleaning processes, however, are relatively low productivity, use of different hazardous chemicals, and high-rate of water consumption. The existing approach is being challenged by the increased concerns expressed by the Department of Energy, the Environmental Protection Agency, and the Food and Drug Administration. Much attention, for example, is being paid to the consequence of pollution caused by the volatile solvents used in cleaning. Because of this, the development of novel, more economical and technologically advanced cleaning technologies has become a major challenge in the engineering community.

In the late of 1970's, commercial high-pressure low-volume waterjet systems were successfully introduced for shaping of hard-to-machine materials, such as steel, alloys, composites, etc.. Waterjets represent a competitive alternative cleaning technology. Various cleaning applications of waterjets are found almost everywhere, from the aerospace industry to water wells and sewer lines. Waterblasting is used to clean tanks, chemical reactors, floors, and grates, unplug tubes, prepare surface for painting, descale billets, remove marine growth, deburr castings, strip off coatings, and more. Globally, waterblasting cleaning constitutes a multi-billon-dollar business. By eliminating the use of solvents, this technology will reduce the cost of cleaning, minimize air pollution, and significantly decrease the volume of liquid waste which must be treated.

Effective waterjet cleaning or coating removal without substrate damage is the most promising direction in the development of the surface processing technology. However, there are several issues to be addressed. There is no systematic and reliable data base describing deposit/coating removal. The present knowledge base consists of mostly unrelated case studies. It is very difficult to apply the acquired information to new cases. Waterjet cleaning consists of several complicated phenomena such as turbulent jet flow, and a large number of variables, for example, water pressure, travel speed, types of nozzle, nozzle body, nozzle diameter, impact angle, coating and substrate properties, etc. are needed to identify these phenomena. It is obvious that a limited number of empirical information is not sufficient to infer a combination of these variables acceptable for a case in question. Despite the obvious demand for this industrial practice, a thorough theoretical base of the cleaning technology has yet to be developed.

Conventional waterjet cleaning is a rapid process which is quite difficult to observe and analyze. Probably, cleaning is due to material erosion by liquid impact and material peeling along the preexisting or initiated macro and micro cracks. Although useful knowledge has been generated by the previous experimental studies, there is no theoretical model capable of integrating this knowledge and presenting it in a form acceptable to practice. There exists no information about the correlation between operation parameters and productivity or standoff distance, which can be used for technology design. The lack of understanding of the process mechanism makes it difficult to utilize the technology's potential. Improvement of the nozzle design, conditions of the jet-workpiece interaction, and even the way of deposit formation will substantially improve the process performance.

A series of experiments were carried out to set up a data base representing waterjet removal of two coatings, oil and epoxy based paints. This data base can be used for waterjet deposit removal in various cases. In order to apply the acquired information to the cleaning of pharmaceutical reactors, removal of aspirin deposit from the material used for the lining of pharmaceutical reactors was examined. Optical and SEM examinations prove that waterjet removal of a coating material can be complete. Phenomena of crack initiation and coating erosion during the waterjet cleaning are explored. It is also shown that under definite conditions, waterjet cleaning will damage a substrate.

In order to identify a safe range of operation conditions in the course of waterjet cleaning, we put forward and define two parameters, critical cleaning standoff distance and critical damage standoff distance, which exist and make effective working space. An economical index, water consumption per unit of cleaned area, is also offered. An improved cleaning technology was used in the course of data acquisition. The improvements include a modification of the nozzle body, use of surfactant and optimization of operating conditions.

Through an analytical and experimental study of cleaning by stationary and moving waterjets, a mathematical model for stationary waterjet cleaning and a semi-empirical model for moving waterjet cleaning are established to express the cleaning width as a function of standoff distance, water pressure, and nozzle size .These models are based on assumptions which are pertinent to waterjet structure and the cleaning mechanism. We assume that removal of coating material by a stationary waterjet occurs when the impact force generated by water droplets exceeds the coating strength due to unlimited impact time. In the course of cleaning by a moving waterjet, the cleaning mechanism is based on Springer's semi-empirical model of material erosion by liquid impacts. According to Springer's erosion mechanism, the material erosion rate is related to the impact force of water droplet, material property, water droplets flow rate, time of impingement, etc.. The maximum cleaning width is shown to exist at a certain standoff distance which is the function of the critical cleaning standoff distance for both cases. The mathematical relations derived are verified experimentally.

A brief summary of the dissertation presentation is given in the following. Chapter 2 gives a general review of cleaning methods and corresponding equipment. Chapter 3 reviews the process of cleaning or material removal, as well as waterjet cleaning mechanisms. Chapter 4 presents an experimental study of cleaning by stationary and moving waterjet. Chapter 5 details the setup, and procedures used in this work for the experimental study of waterjet cleaning. Chapter 6 discusses the theory of turbulent jet, particularly jet structure, and conducts the theoretical investigation of cleaning by the use of a stationary jet. An analytical investigation of moving jet cleaning is described in Chapter 7. An analysis of this investigation is given in Chapter 8. Chapter 9 concludes the research work and provides recommendations for further research.

CHAPTER 2

REVIEW OF CLEANING TECHNOLOGY

2.1 General Description

Cleaning is the removal of an unwanted material from a surface to which it clings. Many methods and techniques have been extensively used in cleaning. General ways of cleaning are usually categorized as follows (Spring, 1974):

1. By detergency;

   Cleaning by detergency is the lifting of the unwanted material from the surface by displacing it with surface active materials which have a greater affinity for the surface than the unwanted material. A detergent such as surfactant or surface active agent has the property of concentrating at surfaces or interfaces because it contains two dissimilar portions in its structure: one having a stronger affinity to the surface of the substrate is soluble in water, and the other can cause modules of the coating close packing to the surfactant modules. Thus, the detergent will result in floating the coating, and the loose coating is readily removed. The selection of the surfactant depends on the property of the substrate and the coating. A good example is using an alkaline cleaner to remove a variety of fatty oil.

2. By solution in a solvent;

   Cleaning by solution in a solvent is dissolving and mixing the solvent with the unwanted material uniformly, which evaporates easily and can be wiped off. Coating types may need special solvent to be dissolved. One of the organic solvents, chlorinated hydrocarbon solvent, can rapidly attack paint.

3. By chemical reaction;

   Cleaning by chemical reaction is yielding soluble or non-interfering products of the unwanted material. Some acid converts iron oxide to a soluble salt while reaction with iron yields hydrogen gas and iron salt.

4. By mechanical removal;

   Cleaning by mechanical removal is wiping or brushing the unwanted material from the surface by machining or abrasion. Waterjet cleaning or material removal is the spraying of parts being carried through a machine equipped with sprays that impinge on the work. Details of this technology will be discussed in Chapter 3. Another example is using mechanical brushes in automobile and railroad cleaning.

The processes described above are not mutually exclusive, and are often used in combination. Usually, industrial cleaning methods are classified as general methods of cleaning and special methods of cleaning.

2.2 Mechanism of Adhesion

Coating or deposit material removal is related to the properties of the coating or deposit material itself, substrate material, as well as the adhesion between the coating and substrate. The adhesive force (Table 2.1) is expressed as the sum of the three components of the attraction between the coating and substrate (Louis and Schikorr, 1982; Hiruma, 1986).

Calculation or direct measurement of adhesion is very difficult, so the cleaning parameters are usually obtained experimentally.

Table 2.1 Adhesive forces

Adhesive Force	Description
Vanderwaals force or specific adhesion (side group-reactions)	The Vanderwaals force is caused by effects of polarization and by electrostatic force between substratum and layer-material. The adhesion may be of middle strength.
Chemosorption (dissociation-force)	Adhesion by chemosorption is due to the emission of free electrons activated from the substrate surface before a chemical reaction to the coating material (cross-linking) during the coating process. The determined adhesion strength are very high.
Mechanical adhesion (gravity, hooked force)	The layer is mechanically fixed in kerf, pores and roughness of the substratum. The rougher the effective surface is, the higher is the degree of adhesion to the layer. The possible adhesion strength reached is relatively low.

2.3 Basic Principles of Industrial Cleaning

The following are generic principles of cleaning:

- Temperature increasing usually improves cleaning.
- Agitation moving the unwanted material improves cleaning.
- A minimum concentration of cleaner is needed; above a critical level cleaning improves when the cleaner concentration increases, but each increment of this concentration has a lesser effect until a point is reached, beyond which increase in concentration has little effect.
- Adequate time must be provided for detergency or reaction of the cleaner with the unwanted material.

- Rinsing away of the unwanted material and cleaner is necessary and must be taken into consideration. This can keep the unwanted materials and cleaner from redepositing on the surface of the substrate.
- The unwanted material redepositing of the work must be prevented.
- The cleaning or solution should not harm the item being cleaned.
- Methods of handling the cleaner depend on the properties of the cleaner.

2.4 General Methods of Cleaning and Equipment

Generally applicable methods and equipment used in industrial cleaning include:

- Immersion or soaking with limited agitation

  Immersion (soaking) cleaning usually works with the parts immersed in the tank filled with the cleaner. The bottom of the tank can be equipped with the agitator to stir up the sludge and debris which overflow away. Steam coils, plate coils, direct-firing burners or immersion electric heaters can be used to aid the cleaning process.

- Spray Cleaning

  Certain pressure cleaners can impinge against the surface of the part through the pipe or nozzle, followed by drain-off to a collecting tank. Parts can be conveyed through the belt, and they need rinsing after spraying.

- Tumbling Barrel or Screw Conveyor Machines

  The tumbling action, combined with rubbing is used to clean the irregular shaped parts which are not effectively cleaned in the immersion tank. This type of cleaning depends on the types of equipment which have three forms:

◊ Rotating barrel in an immersion tank

◊ Tiltable barrel

The parts and cleaner need to be discharged together many times.

◊ Screw conveyor

The conveyor usually operates at low speeds to provide moderate tumbling action to minimize the damage.

- Cleaning by Circulation

This action is based on exposing the part surface to a fresh cleaner rather than on a high level of agitation, which is usually done to clean a large diameter parts such as pipes.

- Brushing

Different types of brushes are used for automobile and railroad cleaning.

- Steam Cleaning with Detergent

This method gives a hot detergent solution mixed with steam under considerable pressure through a gun-like tube ending in a relatively large nozzle. A typical steam cleaner machine pumps water mixed with detergent, under positive pressure, through a heat exchanger which superheats the solution.

2.5 Special Methods of Cleaning and Equipment

Several special methods of cleaning for obtaining high quality clean surface, are introduced in the following:

- Cleaning by Vapor Degreasing

  Cleaning by vapor degreasing is done by introducing the part into a chamber saturated with the vapors of a chlorinated hydrocarbon distilled from a vat of the boiling solvent. This is capable of yielding clean surfaces under controlled conditions.

- Electrocleaning

  The part to be cleaned is made an electrode in a solution of electrolyte. Upon passage of direct current, water is electrolyzed into hydrogen gas at the cathode and oxygen gas at the anode. The generation of gas in large volumes provides a high level of agitation which is prepared to remove the unwanted material.

- Ultrasonic Cleaning

  Ultrasonic cleaning is based on the mechanism of cavitation or collapse of gas bubbles formed by the compression and expansion of the liquid. This high level agitation becomes available through the use of high frequency sound.

2.6 General Methods of Cleanness Evaluation and Examination

Evaluation of cleanliness boils down to rigidly testing those characteristics related to end use. Some such tests from one industry might be used as testing devices in another. Methods of evaluation of cleanliness may be classified as follows:

- Visual Observation

  This requirement would normally have to be fulfilled before any other criteria are applied. Cleanliness can be observed using the naked eye, or by techniques of microscope and electron microscope.

- Wiping

  The wipe test can be easily done using cleansing tissue, filter paper, or a white cloth. This method is especially capable of detecting particulate matter which can be missed by many of the other methods that are more sensitive in other respects.

- Water Break Test

  The water break test is based on the capacity of a metal surface to hold a complete film of water when it is free of oily soil because the surface is hydrophilic. The test is convenient, easy to apply, non-destructive and widely used.

- Spray Pattern or Mist Test

  The surface is sprayed with a mist of clean, cool water through an atomizer. The soiled glass side can be classified if breathed upon. Once discrete droplets condense from the breathed "fog", the side is dirty.

- Atomizer Test

  This test is similar to the spray pattern or mist test, but the difference is that this test is only applied to a dry surface. Usually a dye is added to the spray water to leave a more permanent pattern after drying so that the uncleaned areas can be measured conveniently.

- Fluorescence Test

  A Fluorescence dye is added to the examined surface by exposure of the part to ultraviolet light, followed by photographic or even visual inspection.

- Contact Angle

  By measurements on a droplet of water placed on the part, people can examine the clean surface with the drop flattening out in an almost perfect circle with scalloped edges, and the oily surface with drops not spreading out.

- Radioactive Tracer Test

  The unwanted material is detected after cleaning by measurements with a Geiger Counter in order to find the soils having radioactive components.

- Corrosion Test

  Paper is impregnated with potassium ferricyanide and sodium chloride. Corrosion of the steel yields ferrous ions which react to form a blue deposit of Prussian Blues.

- Gravimetric Tests

  Parts are weighed with analytical balance to exam the weight loss after cleaning.

- Chemical Swab Test

  A piece of sterile absorbent cotton at the end of stick is rubbed over the surface and is then placed in some chemical solvent to exam the ingredient.

- Microbiological Cleanliness Test

  This detection method is similar to chemical swab test but is usually used in testing the bacteria. The collection sample is placed in or on a nutrient medium, growth and reproduction are promoted by incubation until there are enough present be evident as visible.

2.7 Summary

There are many available techniques for cleaning and evaluation of the cleanliness, and a lot of cleaners can be chosen for use. But cost, cleaning time, labor, equipment, detrimental effect, environmental protection, as well as a number of subsidiary factors may need to be balanced against one or another. Sometimes one of these factors is so important that the decision is relatively simple. Of increasing importance is the disposal of wasters from a cleaning operation; this may become a limiting factor in the selection of cleaning materials and may necessitate expensive cartage of chemicals, or equipment to render the waste innocuous. Water has also become expensive and the reduction of its volume may be significant.

CHAPTER 3

HIGH PRESSURE WATERJET CLEANING

Desirable waterjet cleaning is complete coating or deposit material removal without any erosion or damage to the substrate surface using high pressure waterjets (Louis, et al., 1982). In the course of waterjet coating removal, a high speed water stream pressurized previously exits from the nozzle, then impinges on the coating surface and removes the coating materials. It is the combination of water volume and high velocity that does the work of cleaning (Wolgamott, 1993). Waterjet coating removal or cleaning is a highly complex process. The process depends on a number of operation and design parameters which determine, such as jet structure, interaction between waterjet and coating and between substrate and coating, etc.. It is believed that erosion is the dominant reason for material removal by waterjets. Since waterjet cleaning has become more and more useful, understanding of the mechanism of this technology is necessary.

3.1 Applications of Waterjet Cleaning

Pure waterjets have been widely used for various cleaning applications such as the removal of different coatings or deposits from the substrate. Singh, et al. (1992) and Watson, et al. (1993) applied ultra-high pressure water jets to remove thermal spray during aircraft engine overhaul. The use of chemical solvents was eliminated. Conn (1992) discussed the use of water servojet in cleaning coke oven doors in a steel mill, cleaning Teflon filter mandrels and removal of cement-builders from railroad hopper cars. Minden, et al. (1990); Hofacker (1993); Leu, et al. (1994); Geskin, et al. (1995, 1996) and Meng, et al. (1995, 1996a, 1996b, 1996c) discussed their experience in waterjet paint removal. Xue, et al. (1993), Conn and Chahine (1985) described applications of waterjet in rust removal from the ship hull. Louis et al. (1984) discussed cleaning of polymeric model layers. Also Vijay (1989) reviewed waterjet medical applications such as wound cleaning and oral hygiene. A General summary of the waterjet cleaning and decoating was made by Schikorr and Louis (1982); Summers (1993) and Wolgamott (1993) as follows (Table 3.1):

3.2 Parameters of Waterjet Cleaning

The effects of various parameters on the results of waterjet cleaning are discussed by a number of researchers. (Springer, 1976; Hashish and duPlenssis, 1978; Kim and Labus, 1993; Wu and Kim, 1995; Leu, et al., 1994; Geskin, et al., 1995; Meng, et. al., 1995, 1996a, 1996b, 1996c). Table 3.2 summarizes this discussion.

3.3 Mechanism of Waterjet Cleaning

In the course of waterjet cleaning, the continuous water flow exiting from the nozzle gradually becomes a stream of water droplets. This disintegration is due to a continuous interaction between the water and surrounding air (Chapter 6). Water droplets impinging a target create impact forces. The impinged area of the substrate surface experiences repeated impacts of the droplets. This enables coating removal from the substrate. It has

Table 3.1 Industrial applications of waterjet cleaning and material removal

INDUSTRY	APPLICATIONS
Airport	Grease, rubber and hydraulic fluids on runways, joint, air craft paint removal
Aluminum	Hardened bauxite dust on mills, filters, digesters, tanks, sumps and sewers
Automobile	Washing and deburring
Automotive	Paint and solder from booths, conveyor, machinery, grating, and vent stacks
Cement	Hopper cars, bins, floors, walls, rotary kilns, cooler hearths, and preheaters
Construction	Concrete, tar, asphalt, mortar, dirt, grease, and clay on vehicles, mix trucks, machinery, exposing aggregate in dams, lifts, canals, runways prior to pours, and laitent removal
Chemical Process	Chemicals from tube bundles, boiler tubes, heat exchangers, tanks, pipe, vessels, valves, evaporators, reactors and facility, and electrolytic plates
Foundries	Removal of metal oxidation, deposits, and from castings, furnaces and paddles
Highways	Mud, grease, tar, cement or asphalt on vehicles and machinery, tar and mastic on concrete, expansion joints, paint stripes, unplug culverts, strip old coatings, and prepare railings for paint
Manufacturing	Materials and parts cleaning, deburring, surface preparation and paint booth and stack cleaning, removal of adhesive forming-material
Marine	Barnacles, marine growth, loose paint and rust on ship hulls, platforms, docks, ballast, storage, tanks, boiler and underwater cleaning of pipe and platforms
Metal Working	Mill scale, tight rust and weld slay from new vessels, pipe and tanks, deburring, and parts cleaning
Mining	Clogged plant machinery and premaintenance cleaning of dampers, drag lines, and conveyor systems
Municipalities	Sewers and drain pipes, sanitation equipment and refuse vehicles, reservoirs and building restoration, damaged and worn walls
Nuclear Plants	Precleaning, decontamination or equipment before maintenance and "U" tube heat exchangers
Oil Field	Paraffin and crude residues on platforms and storage tank, drilling mud and cement from drill pipe, downhole cleaning and unplugging with coil tubing
Petrochemical	Scale and deposit on heat exchangers, reactors, tanks, cooling towers, pipes and facilitates
Pharmaceutical	Chemicals from kettles, pipe, tubes, mixers, heat exchangers, reactors, filters and evaporators
Pipe Yard	Rust and varnish prior to recoat, dope and oil from pipe threads, drilling mud and internal debris
Power Station	Flyash from preheaters, slag from burners, cyclones, boilers, and superheaters
Pulp & paper	Black liquor, pulp, pitch from heat exchangers, tube, presses, suction rolls and stock chests and lines, photosensitive layer
Railroad	Potash, gypsum, cement, lime in hopper cars, grease, truck undercarriages and cars
Refineries	Coke, scale, hard carbon and polymers in heat exchangers, pipe, tubes and tanks
Rubber	Latex, chemigum, water scale in reactors, storage tanks, conveyors, heat exchangers, rubber-roller, pipe and tubing
Saw-mills	Cutting-off the bark of the tree-trunks
Steel mill	Coke and slay from heat exchangers, boilers, furnaces, chutes and hoppers
Surface preparation	Rust, paint, elastomer castings, refractory buildup, wet sandblasting, and soluble abrasive blasting
Water Wells	Remove deposits and buildups from screens, and open up gravel pack

Table 3.2 Parameters of waterjet cleaning and material removal

Parameters of Jet		
	(1)	Velocity of droplet and distribution
	(2)	Droplet Size and distribution
	(3)	Droplet concentration
	(4)	Density of liquid
	(5)	Velocity of a compressive wave
	(6)	Liquid Property
	(7)	Temperature
Parameters of Jet System		
	(1)	Jet source pressure
	(2)	Standoff distance
	(3)	Jet travel speed
	(4)	Nozzle diameter
	(5)	Type of nozzle
	(6)	Diameter of mixing or focusing tube
	(7)	Type of mixing or focusing tube
	(8)	Length of mixing or focusing tube
	(9)	Type of nozzle body
	(10)	Time of duration
	(11)	Mass fluid rate
Impact Parameters		
	(1)	Impact velocity
	(2)	Impact angle
	(3)	Impact coefficient
Parameters on Coating and Substrate		
	(1)	Density
	(2)	Velocities of the compression and shear waves
	(3)	Modules of elasticity
	(4)	Poisson's ratio
	(5)	Endurance limit
	(6)	Ultimate tensile strength
	(7)	Compressive and shear strength
	(8)	Fracture toughness
	(9)	Hardness
	(10)	Grain size
	(11)	Surface roughness
	(12)	Defection
	(13)	Curvature of surface
	(14)	Thickness
Adhesion Properties		
	(1)	Adhesion strength
Others		
	(1)	Effect of outside aid like surfactant
	(2)	Temperature

been reported that erosion is the dominant mechanism for material removal. The erosion is generally initiated by macro or micro cracks caused by the impact forces from the water droplets (Springer, 1976; Erdmann-Jesnitzer, et al., 1978; Louis and Schikorr, 1982; Haferkamp, et al., 1984; Ramulu, et al., 1991; Li, et al., 1992; Kang, et al., 1993; Watson, 1993).

Material failure during waterjet cleaning may occur in the coating, in the substrate or in the coating-substrate interface (Springer, 1976). Adler (1979) reported that material removal by waterjets consists of four primary damage modes: direct deformation, stress wave propagation, lateral outflow jetting, and hydraulic penetration. The first two modes are responsible for initiation of cracks in the material to be removed. Lateral outflow jetting does not contribute to the initiation of cracks but can lead to the extension and enlargement of pre-existing cracks. Hydraulic penetration could cause propagation of existing cracks. One or more damage modes may coexist in a particular erosion process, which is material dependent. Coating materials may be brittle or ductile. Brittle materials are shown to fail first at the surface immediately with the cracks being initiated and propagated, and with the absence of a deformation area at the crack tip. Cracks initiated can run a small distance or a large distance which result in small or large piece of coating removal. Ductile materials are found to fail below the surface with no apparent failure on the surface. These materials posses the ability to deform under the influence of externally applied pressures, and significantly higher impact pressure is shown to cause a ductile solid to deform as a highly viscous liquid, (Peterson, 1973; Field, at el., 1979, 1983; Erdmann-Jesnitzer, et al., 1980; Evans, et al., 1979, 1983; Wu and Kim, 1995). In the coating material removal, the adhesive situation between the coating and substrate must also be considered.

Erosion by liquid impacts was theoretically investigated by Springer (1976). He found material erosion to be related to impact velocity and material property, and used a semi-empirical model to describe the coating erosion behavior (i.e. mass erosion rate, etc.). Based on the idea that fatigue plays an important role in the erosion process, he used the fatigue theorem of repeated bar torsion and bending to yield the quantitative results of material erosion by repeated impacts of liquid droplets with an assumption that the two failure mechanisms are sufficiently similar.

3.4 Previous Study of Waterjet Cleaning and Material Removal

To date, a number of investigations of waterjet cleaning have been so far reported. Explanation of the correlation between process parameters and performance was based on the various experimental observations. The parameters in question include water pressure, travel speed, nozzle size, jet structure, and standoff distance. These are the key operation parameters in the processes of waterjet cleaning or material removal (Singh, et al., 1992; Wu and Kim, 1995). The previous studies on parameters investigation are summarized and discussed below:

3.4.1 Water Pressure

It was found that there exists a threshold pressure, below which no material removal occurs no matter how large a water flow rate is and how long a process duration is

(Erdmann-Jesnitzer, et al., 1980; Minden, et al., 1990; Singh, et al., 1992; Wu and Kim, 1995). Water pressure determines jet velocity and turbulent properties, which may influence on jet cleaning. When water pressure increases, material removal rate, cleaning width and depth also increase, as it was shown in various experimental studies (Galecki and Vicker, 1982; Haferkamp, et al. 1984; Singh, et al., 1992; Kang, et al. 1993; Xu and Summers; 1994; Leu, et al.; 1994; Geskin, et al., 1995, 1996; Wu and Kim, 1995; Meng, et al., 1995, 1996a, 1996b, 1996c).

3.4.2 Travel Speed (traverse rate)

Investigations of correlation between cleaning width and depth with process conditions were discussed by Hilaris and Labus, (1978); Hashish and duPlessis, (1978); Saunders and Barton, (1986); Singh, et al., (1992); Leu, et al., (1994); Xu and Summers, (1994); Wu and Kim, (1995); Hlavac, (1995); Geskin, et al., (1995); Meng, et al., (1995, 1996a, 1996b, 1996c). These experimental results show that width or depth of material removal decrease with the increase of travel speed. An increase of travel speed may result in a decrease of energy or drople tnumbers which are delivered per unit of coating area. Singh, et al., (1992) discussed complete coating removal envelop at various travel speeds for a given standoff distance and pressure. Traverse speed during decoating is divided into three regions: incomplete coating removal, complete coating removal, and substrate damage.

3.4.3 Nozzle Type

There are two types of commonly used nozzles, round-jet nozzles, and flat-jet nozzles. The jet out of a round-jet nozzle is in the shape of rotational symmetry, which is to minimize the divergence of the round-jet to reach a good efficiency at a greater distance from the nozzle. Contrary to this, the flat-jet enlarges only in one direction, the divergence orthogonal to this direction is less. Flat-jets are used in smaller distances from a nozzle to load large area (Louis and Schikorr, 1982). Harbaugh and Fincher (1993) designed a specific nozzle for complex surfaces with improvement of jet coherency and higher energy. This nozzle improvement was attained due to a combination of flat and round nozzles with translation and rotation around the centerline. A Similar application was once mentioned by Saunders and Barton, (1986). A Long cohesive nozzle is used to form the jet without losing energy. Fan jets work better at low travel speed compared to a round jet and a shorter standoff distance for removal of a large area (Wu and Kim, 1995; Xu et al. 1994). Multiple-orifice of small size, which may be preferable to single-orifice of large nozzle with more efficiency of energy distribution, works more effectively (Waston, 1993, Harbaugh, 1993; Gracey, 1989), but cleaning quality may not be as good in the swirl patterns due to the possible weakening jet (Singh, et al., 1982).

3.4.4 Nozzle Diameter

At a given pressure, large nozzles are more efficient than smaller ones. Experimental results have shown that width and depth of decoationg, and thus material loss increase with the increase of nozzle diameter (Wu and Kim, 1995). Similar results are also shown in the experimental studies of Watson, (1993); Leu, et al., (1994); Malavc, (1995); Geskin, et al., (1995, 1996) and Meng, et al., (1995, 1996a, 1996b, 1996c).

3.4.5 Modification of Jet

Jet structure and properties could be modified through formation of the resonant cavity, addition of outside oscillation, etc.. Applications of several special jets are discussed below:

Percussive jet impact has various favorable features for material removal, such as increased impact area per unit of water volume, repetitive initial-impact water hammer pressure, and high lateral outflow velocity (Nebeker and Rodriguez, 1976). The use of the specially designed oscillating device show that a significant drop of power input for the same work can be achieved when the water jet is oscillated either in the direction of the feed or perpendicular to this direction for paint removal. The oscillation in the same direction of the feed, improves the water jet performance due to the increased number of water passes on the same surface region (Veltrup, 1976; Erdmann-Jesnitzer, et. al., 1976), Using a cavitating waterjet to remove marine fouling and rust from the surface can reduce the power significantly, and the cavitating jets can also provide faster rates of cleaning or cutting in comparison to a conventional waterjet (Conn, et. al., 1976, 1984). A self-resonating nozzle has been found to have higher inceptions for cavitation than conventional in cleaning. Self-resonating cavitating and pulsed jets can be obtained through nozzle or nozzle body design and improvement to reach better stripping efficiency which were mentioned by Conn (1982, 1992), and similar tests were made by Hiruma et al. (1986); Saunders et al. (1986) and Sanders et al. (1984).

3.4.6 Standoff Distance

A new concept of critical cleaning standoff distance was first reported by Leu, et al., (1994), then discussed by Geskin, et al., (1995, 1996) and Meng, et al., (1995, 1996a, 1996b, 1996c). This concept implies that there exits a standoff distance, above which the cleaning becomes ineffective. A similar concept of effective standoff distance was also used in the selection of the standoff distance in jet cleaning (Wu and Kim, 1995). Experimental observations have shown that there exists an optimal standoff distance at which the volume of material removal is the greatest at a given travel speed (Louis and Schikorr, 1982; Kang, et al., 1993). They have also shown that the cleaning rate increases with the increase in standoff distance until it reaches the maximum at a certain standoff distance, after that the cleaning rate declines with increased standoff distance (Hashish and duPlessis, 1978; Galecki and Vickers, 1982; Haferkamp, et. al. 1984; Leu, et al., 1994; Xu and Summers, 1994; Geskin, et al., 1995; Wu and Kim, 1995). The optimal standoff distance is related to coating and substrate materials, jet structure and properties, and operation parameters such as nozzle size, water pressure, travel speed, etc.. Wu and Kim (1995) commented that it is difficult to determine an optimum standoff distance for universal use due to the effects of a number of parameters. Until recently, Meng, et al., (1996b, 1996c) firstly introduced mathematical models for the evaluation of the optimal standoff distance for the cases of stationary and moving waterjet cleaning. This analysis was verified experimentally.

3.4.7 Mixing Chamber

Use of an integral small attenuation chamber loaded above the orifice, was reported to improve stream quality and deliver maximum stripping at fixed flow rate (Johnson, 1993).

3.4.8 Surfactants

Duration of the jet-surface interaction is in an order of 0.0001~0.001 seconds. This time is too short for completion of chemical reaction. The chemical should therefore be applied to the surface before impact (Summers, 1993), but surfactant added in the jet can provide corrosion inhibition on the cleaned surface (Hall, 1986). The effect of the surfactant (1% FC-722) coating surface pretreatment was tested and reported by Geskin, et al., (1995), which proved that good cleaning performance could be achieved by this method.

3.4.9 Economics

Comparison of the economics of waterjet cleaning with those of grit blasting in rust removal is given by Conn, (1985) and Shunk, (1995). This study suggested using water consumption as a criterion for the evaluation of the cleaning process. It not only represents the cost factor, but also reflects wastage creation during the cleaning itself

(Leu, et al., 1994; Geskin, et al., 1995, 1996; Meng, et al., 1995, 1996). Similar analysis was also presented by Remisz (1993).

3.4.10 Other Factors

The use of high temperature water as opposed to cold water is more effective in removing the grease (Summers, 1982), and temperature influence on the jet cleaning or material removal process was mentioned by Neusen and Schramm, 1978; Louis and Schikorr, 1982. Improvement of the nozzle geometry (l/d ratio and conical angle) may influence on jet cleaning or material removal rate (Minden, et al., 1990, Bury, et al., 1974). Of course, past or present investigation of other factors can be found in the literature concerned.

3.5 Summary

Although useful knowledge has been generated from various experimental studies previously done, understanding of waterjet cleaning is still insufficient.. This study addresses several concerns needed to improve the understanding of the process.

1. Effective cleaning region determined by critical cleaning and damage standoff distances was not clearly defined and investigated with relation to the operation parameters. This was first reported by Leu, et al., 1994, then discussed and investigated by Geskin, et al., 1995, 1996 and Meng, et al., 1995, 1996a, 1996b, 1996c).
2. Water consumption is not only related to the cost, but also to the wastage creation. This was not clearly defined and investigated previously. Correlation between water

consumption and other parameters was not identified (this was first defined and reported by Leu, et al., 1994, then discussed by Geskin, et al., 1995, 1996 and Meng, et al., 1995, 1996a).

3. Development and improvement of waterjet cleaning technology to achieve good cleaning performance is important, and can be attained through modification of the jet formation or surfactant treatment of coating surface before cleaning.

4. Waterjet cleaning technology can be developed empirically through systematic investigation of influence of various parameters on the cleaning performance, but the present knowledge is not sufficient for such a development.

5. There is no theoretical model which is capable of explaining the observed experimental results and optimizing process conditions (until recently, Meng, et al., 1996b, 1996c made the first attempt to establish mathematical models of stationary and moving waterjet cleaning processes, respectively).

CHAPTER 4

EXPERIMENTAL STUDY OF WATERJET CLEANING

A series of experiments have been conducted to investigate the waterjet cleaning processes, as well as the performances of cleaning influenced by various parameters. These parameters include types of coating and substrate materials, pressure, travel speed, nozzle diameter, standoff distance, surfactant treatment of coating surface, and modification of the jet structure through improvement of nozzle body design. The parameters in question and range of their variations are listed in Table 4.1. Evaluation of the cleaning performance is listed in Table 4.2, The phenomena of erosion leading to coating removal and substrate damage by waterjets are given in Table 4.3. Cleaning results will be presented and analyzed in Chapter 8.

Table 4.1 Parameters of waterjet cleaning

Parameter	Unit	Description
Type of Coating		Oil-based paint, epoxy-based paint, aspirin deposit (a), rust.
Type of Substrate		AISI1018 (low carbon steel), glass lined #3008.
Type of Nozzle Body		Conventional, modified, spiral.
Nozzle Diameter	mm (in, No.)	0.1778 (0.007, 7), 0.254 (0.010, 10), 0.3048 (0.012, 12), 0.3556 (0.014, 14)
Pressure	MPa (psi)	0 (0) ~ 311 (45,000)
Travel Speed	m/min. (in/min.)	0 (0) ~ 25.5 (1000)
Focusing Tube	mm (in, No.)	0.762 (0.030, 30), 0.8382 (0.033, 33), 1.62 (0.063, 63), 2.362 (0.093, 93)
Standoff Distance	m (in)	Measured, set
Surfactant		FC-722
Thickness of Coating		Measured

Table 4.2 Criteria of waterjet cleaning performance

Criterion	Unit	Coating
Cleaning Width	mm	Oil-based paint, epoxy-based paint, aspirin deposit (a).
Cleaning Rate	m^2/h	Oil-based paint, epoxy-based paint, aspirin deposit (a).
Water Consumption	m^3/m^2	Oil-based paint, epoxy-based paint, aspirin deposit (a).

Table 4.3 Phenomena of coating and substrate erosion by waterjet

Erosion	Material	Phenomena
Coating	Oil-based paint	Crack, erosion
	Epoxy-based paint	Mussel-like erosion
Substrate	Glass-lined #3008	Break, surface erosion
	Transparent glass	Crack, pit on surface
Coating with Surfactant Surface Treatment	Epoxy-based paint	crack

4.1 Parameters Investigation

Experimental investigation of process parameters demonstrates that the standoff distance is a critical control variable. An excessive standoff distance results in ineffective cleaning, while an insufficient standoff distance might bring about substrate damage. We use the terms "*critical cleaning standoff distance*" and "*critical damage standoff distance*" to capture these effects. These notions were firstly put forward by Leu, et al., (1994), then investigated and discussed by Geskin, et al., (1995, 1996), and Meng, et al., (1995, 1996 a, 1996b, 1996c).

4.1.1 Critical Cleaning Standoff Distance

The basic goal of waterjet cleaning is complete coating/deposit removal without any damage to the substrate surface. It has been observed that there exists a certain standoff distance above which the coating or deposit can not be effectively removed. Thus, beyond this critical standoff distance cleaning becomes ineffective because waterjet energy gradually decays with increased standoff distance. We term this standoff distance as the "*critical cleaning standoff distance*". This critical cleaning standoff distance was found experimentally to be related to the parameters of coating and substrate, water pressure, nozzle diameter, jet structure, travel speed, and focusing tube diameter, and also theoretically proven to be related to travel speed, water pressure, nozzle diameter, and jet structure. Investigation of the critical cleaning standoff distance was carried out with a series of experiments, which are categorized in different groups shown in Table 4.4.

4.1.2 Critical Damage Standoff Distance

The term "*critical damage standoff distance*" is introduced to emphasize that damage may occur when the standoff distance is insufficient. Although the yield strength of the substrate material in waterjet cleaning is usually much higher than that of the coating material, the energy of the waterjet may be so powerful that it can cause damage to the substrate surface if the surface is very close to the jet exit. Investigation of critical damage standoff distance was tested with experiments, which are shown in Table 4.5. The samples were examined using an optical microscope for the study of waterjet erosion.

Table 4.4 Investigation of critical cleaning standoff distance

Group No. of Experiment (Status)	Coating	Substrate	Pressure (MPa)	Travel Speed (m/min.)	Nozzle Diameter (No.)	Focusing Tube Diameter (No.)	Type of Nozzle Body
1 (Moving)	Oil-based paint	AISI1018	69 ~ 311	1.27 ~ 25.4	7, 10, 12, 14	30, 33, 63, 93	Conventional, modified, spiral
2 (Moving)	Epoxy-based paint	AISI1018	69 ~ 311	1.27 ~ 25.4	7, 10, 12, 14	30, 33, 63, 93	Conventional, modified, spiral
3 (Moving)	Epoxy-based paint	Glass-lined #3008	207	2.54 ~ 25.4	14	63	Modified
4 (Stationary)	Oil-based paint	AISI1018	104 ~ 311	0	7, 10, 12, 14		Modified
5 (Stationary)	Oil-based paint	AISI1018	242 ~ 311	0	12, 14	63, 93	Modified
6 (Moving)	Oil-based paint	AISI1018	69 ~ 276	2.54 ~ 25.4	7, 10, 12, 14		Modified
7 (Moving)	Oil-based paint	AISI1018	207 ~ 276	2.54 ~ 25.4	7, 10 12, 14	63, 93	Modified
8 (Stationary)	Epoxy-based paint	AISI1018	104 ~ 311	0	12, 14		Modified
9 (Stationary)	Epoxy-based paint	AISI1018	242 ~ 311	0	12, 14	63, 93	Modified
10 (Moving)	Epoxy-based paint	AISI1018	69 ~ 276	2.54 ~ 25.4	7, 10, 12, 14		Modified
11 (Moving)	Epoxy-based paint	AISI1018	207 ~ 276	2.54 ~ 25.4	12, 14	63, 93	Modified

Table 4.5 Investigation of critical damage standoff distance

Group No. of Experiment	Substrate	Pressure (MPa)	Travel Speed (m/min.)	Nozzle Diameter (No.)	Focusing Tube (No.)	Type of Nozzle Body
1 (Moving)	Glass-lined #3008	204 ~ 311	0.635 ~ 15.24	10, 12, 14	63, 93	Modified

4.1.3 Effective Working Space for Waterjet Cleaning

An area on the substrate surface where the coating is completely removed without any substrate damage by the impinging waterjet is termed "*Effective working space for waterjet cleaning*". So actually the effective working space is enveloped by the critical cleaning standoff distance and the critical damage standoff distance. These two critical standoff distances also divide the entire space into three regions, namely, incomplete coating removal, effective working space for complete coating removal, and substrate damage. The experimental investigation on effective working space is based on Experimental Group No. 3 in Table 4.4 and Experimental Group No. 1 in Table 4.5.

4.1.4 Optimal Cleaning Standoff Distance

Optimal cleaning standoff distance which is responding to the maximum cleaning width occurred with coating removal by waterjet, is existed. In practice, this standoff distance should be located in the effective working space because it is possible to cause the damage to the substrate if it is too close to the nozzle exit. Testing the optimal cleaning standoff distance is made for different types of coatings under various operation conditions, which are listed in Table 4.6.

4.1.5 Effect of Surfactant Pretreatment

The effect of coating surface pretreatment with a surfactant on waterjet cleaning was studied. Surfactants were deposited on the substrate surface prior to cleaning. Another experimental procedure involved the addition of a surfactant into water prior to the compression in the intensifier. The results of the investigation of the effect of surfactant pretreatment are shown in Table 4.7.

Table 4.6 Investigation of optimal cleaning standoff distance

Group No. of Experiment (Status)	**Coating**	**Substrate**	**Pressure (MPa)**	**Travel Speed (m/min.)**	**Nozzle Diameter (No.)**	**Focusing Tube Diameter (No.)**	**Type of Nozzle Body**
1 (Moving)	Oil-based paint	AISI1018	69 ~ 311	1.27 ~ 25.4	7, 10, 12, 14	30, 33, 63, 93	Conventional, modified, spiral
2 (Moving)	Epoxy-based paint	AISI1018	69 ~ 311	1.27 ~ 25.4	7, 10, 12, 14	30, 33, 63, 93	Conventional, modified, spiral
3 (Stationary)	Oil-based paint	AISI1018	104 ~ 311	0	7, 10, 12, 14		Modified
4 (Stationary)	Oil-based paint	AISI1018	242 ~ 311	0	12, 14	63, 93	Modified
5 (Moving)	Oil-based paint	AISI1018	69 ~ 276	2.54 ~ 25.4	7, 10, 12, 14		Modified
6 (Moving)	Oil-based paint	AISI1018	207 ~ 276	2.54 ~ 25.4	12, 14	63, 93	Modified
7 (Stationary)	Epoxy-based paint	AISI1018	104 ~ 311	0	7, 10, 12, 14		Modified
8 (Stationary)	Epoxy-based paint	AISI1018	242 ~ 311	0	12, 14	63, 93	Modified
9 (Moving)	Epoxy-based paint	AISI1018	69 ~ 276	2.54 ~ 25.4	7, 10 12, 14		Modified
10 (Moving)	Epoxy-based paint	AISI1018	207 ~ 276	2.54 ~ 25.4	12, 14	63, 93	Modified

Table 4.7 Investigation of effect of surfactant on critical standoff distance

Group No. of Experiment	Coating	Substrate	Operating Parameters	Surfactant (1% FC-722)	Time of Surfactant Treatment (h)
1 (Moving)	Epoxy-based paint	AISI1018	Travel speed: 10.16 m/min., nozzle body: modified, nozzle No.: 14, focusing Tube No.: 63 pressure: 172 MPa	Coating surface preferment	0, 0.03, 0.5, 2, 5, 24
2 (Moving)	Epoxy-based paint	AISI1018	Travel speed: 10.16 m/min., nozzle body: modified, nozzle No.: 14, focusing Tube No.: 63 pressure: 172 MPa	Mixed with water resource in the tank	

4.2 Investigation of Waterjet Cleaning Performance

Three criteria, cleaning width, cleaning rate, and water consumption, have been investigated for the evaluation of waterjet cleaning performance. Cleaning width and maximum cleaning width, are closely correlated with operational parameters as well as properties of coatings and substrates Cleaning rate is a linear function of the cleaning width related. This work firstly used the term "*water consumption*" as a the criterion for the evaluation of the cost of cleaning and wastage generation.

4.2.1 Cleaning Width and Maximum Cleaning Width

Investigation of the effect of operation parameters, coating and substrate properties on the cleaning width variation is a main task of our research. Various tests were systematically carried out to acquire information necessary for the evaluation of the desired correlation. The investigation of parameters on cleaning width and maximum cleaning width is listed in Table 4.8.

Table 4.8 Investigation of cleaning width & maximum cleaning width

Group No. of Experiment (Status)	Coating	Substrate	Pressure (MPa)	Travel Speed (m/min.)	Nozzle Diameter (No.)	Focusing Tube Diameter (No.)	Type of Nozzle Body
1 (Moving)	Oil-based paint	AISI1018	69 ~ 311	1.27 ~ 25.4	7, 10, 12, 14	30, 33, 63, 93	Conventional, modified, spiral
2 (Moving)	Epoxy-based paint	AISI1018	69 ~ 311	1.27 ~ 25.4	7, 10, 12, 14	30, 33, 63, 93	Conventional, modified, spiral
3 (Stationary)	Oil-based paint	AISI1018	104 ~ 311	0	7, 10, 12, 14		Modified
4 (Stationary)	Oil-based paint	AISI1018	242 ~ 311	0	12, 14	63, 93	Modified
5 (Moving)	Oil-based paint	AISI1018	69 ~ 276	2.54 ~ 25.4	7, 10, 12, 14		Modified
6 (Moving)	Oil-based paint	AISI1018	207 ~ 276	2.54 ~ 25.4	12, 14	63, 93	Modified
7 (Stationary)	Epoxy-based paint	AISI1018	104 ~ 311	0	7, 10, 12, 14		Modified
8 (Stationary)	Epoxy-based paint	AISI1018	242 ~ 311	0	12, 14	63, 93	Modified
9 (Moving)	Epoxy-based paint	AISI1018	69 ~ 276	2.54 ~ 25.4	7, 10, 12, 14		Modified
10 (Moving)	Epoxy-based paint	AISI1018	207 ~ 276	2.54 ~ 25.4	12, 14	63, 93	Modified
11 (Moving)	Aspirin (a)	Glass-lined #3008	138	10.16	14	93	Modified

4.2.2 Effect of Surfactant Treatment

The effect of coating surface pretreatment with surfactant under different duration is studied. Also studied is the effect of surfactant premixed with resource water in the tank. Investigation of the effect of surfactant on cleaning width is listed in Table 4.9.

Table 4-9 Investigation of effect of surfactant on cleaning width

Group No. of Experiment	Coating	Substrate	Operating Parameters	Surfactant (1% FCC-722)	Duration of Surfactant Treatment (h)
1 (Moving)	Epoxy-based paint	AISI1018	Travel speed: 10.16 m/min., nozzle body: modified, nozzle No.: 14, focusing Tube No.: 63	Coating surface pretreatment	0.03, 0.5, 2, 5, 24
2 (Moving)	Epoxy-based paint	AISI1018	Travel speed: 10.16 m/min., nozzle body: modified, nozzle No.: 14, focusing Tube No.: 63	Mixed with water resource in the tank	

4.2.3 Cleaning Rate

The rate of cleaning is an important criterion determining the effectiveness of waterjet decoating. Cleaning rate for a single jet, is defined as follows:

$$\text{Cleaning Rate (m}^2\text{/h)} \quad H = wV \,{*}(0.06 \text{ m min./mm h}) \qquad (4.1)$$

where w is cleaning width (mm), and V is travel speed (m/min.).

It can be seen that cleaning rate is cleaning width and the corresponding travel speed related. The cleaning rate increases as the cleaning width or the travel speed increases. Except for stationary situations, the cleaning rate can be calculated by the use of information presented in Table 4.8.

4.2.4 Water Consumption

Another important criterion determining the effectiveness of waterjet cleaning is volumetric water consumption per unit of the cleaned area. Higher water consumption not only results in a higher cleaning cost, but also brings about environmental problem. Disposing contaminated water is expensive and an environmental damaging process. Water consumption is defined as follows:

$$\text{Water Consumption } (m^3/m^2)\ K = \frac{I}{H} \qquad (4.2)$$

where I is volumetric water consumption (m/h), which is obtained by multiplication of the time spent and mass flow rate, detail measurement (refer to Chapter 5.6) for different pressures and nozzle diameters is based on Table 4.8.

4.3 Investigation of Coating Erosion by Waterjet

Coating erosion by waterjets was investigated in order to explore the mechanism of waterjet coating removal. Investigation is carried out according to Table 4.10.

Table 4.10 investigation of effect of coating erosion by waterjet

Group No. of Experiment	Coating	Substrate	Pressure (MPa)	Travel Speed (m/min.)	Nozzle Diameter (No.)	Focusing Tube Diameter (No.)	Type of Nozzle Body
1 (Moving)	Oil-based paint	AISI1018	69 ~ 311	2.54 ~ 25.4	7, 10, 12, 14	33, 63, 93	Modified, spiral
2 (Moving)	Epoxy-based paint	AISI1018	69 ~ 311	2.54 ~ 25.4	7, 10, 12, 14	33, 63, 93	Modified, spiral
3 (Moving, surfactant surface pretreatment)	Epoxy-based paint	AISI1018	172	10.16	7, 10, 12, 14	63	Modified

4.4 Summary

The discussions above outline the architecture of the study reported in this dissertation. The performed experimental study was decomposed into several substudies with individual objectives, but with a common mission. The details of experimental procedures, examination and measurement will be discussed in Chapter 5, and experimental results, as well as analysis will be presented in Chapter 8.

CHAPTER 5

EXPERIMENTAL SETUP, METHODS AND EXAMINATION

5.1 Waterjet Cleaning System

The cleaning experiments with stationary and moving jet were carried out with an Ingersoll-Rand waterjet system (Fig. 5.1). The cleaning head is mounted on a 5-axis gantry robot whose movement is controlled by an Allen Bradley 8200 series CNC controller. The translation along the X-axis is controlled by a rack and pinion system, and the translation along the Y- and Z- axes are controlled by two motorized ball-screws. Two rotary axes, one in the horizontal (i.e. the pitch motion) and the other one in the vertical direction respectively (i.e. the roll motion), permit angular displacements between 200 and 360 degrees.

The high pressure water supply system includes a water softener, a booster pump, and an intensifier. The water softener is used to remove the iron and calcium, and dissolve solids that will cause damage to the sapphire nozzle. Then softened water is fed to the booster pump which produces the pressure of 10.4 MPa (1,500 psi), then this water is further pressurized by an intensifier using a hydraulically driven, double acting, reciprocating plunger pump and carried through a stainless steel pipe to the cleaning head (Fig. 5.2). The pressure of water can be increased to as high as 414 MPa (60,000 psi), and the maximum operating pressure of the intensifier is maintained at 345 MPa (50,000 psi).

The intensifier system also contains a water accumulator that is used to reduce pressure pulsation at the nozzle.

5.2 Nozzle, Focusing Tube and Nozzle Body

Four different diameters of round sapphire nozzles, four different diameters of focusing tubes, and three different nozzle bodies were used in the experiments. Nozzle nos. 14, 12, 10 and 7 were used, which correspond to the nozzle diameters of 0.014, 0.012, 0.010 and 0.007 inches, respectively. The focusing tubes are made by carbide with 2 inches in length each. The used are nos. 30, 33, 63, and 93, which correspond to the tube diameters of 0.030, 0.033, 0.063, and 0.093 inches, respectively. Using a focusing tube is aimed at increasing watejet core length and width. Involved in the tests are three types of nozzle bodies: the conventional, modified, and spiral ones. Fig. 5.3(a) shows the conventional nozzle body. To modify the jet stream, we have taken two approaches to replace the conventional nozzle body. The first one is to block the inlet nipple as shown in Fig. 5.3(b). By this modification, the jet is expected to have more uniform vortex density and water pressure distribution. The second approach is to modify the jet flow by using a spiral body placed inside the nozzle body as shown in Fig. 5.3(c). Through this modification, a wider jet formation (jet width) is expected.

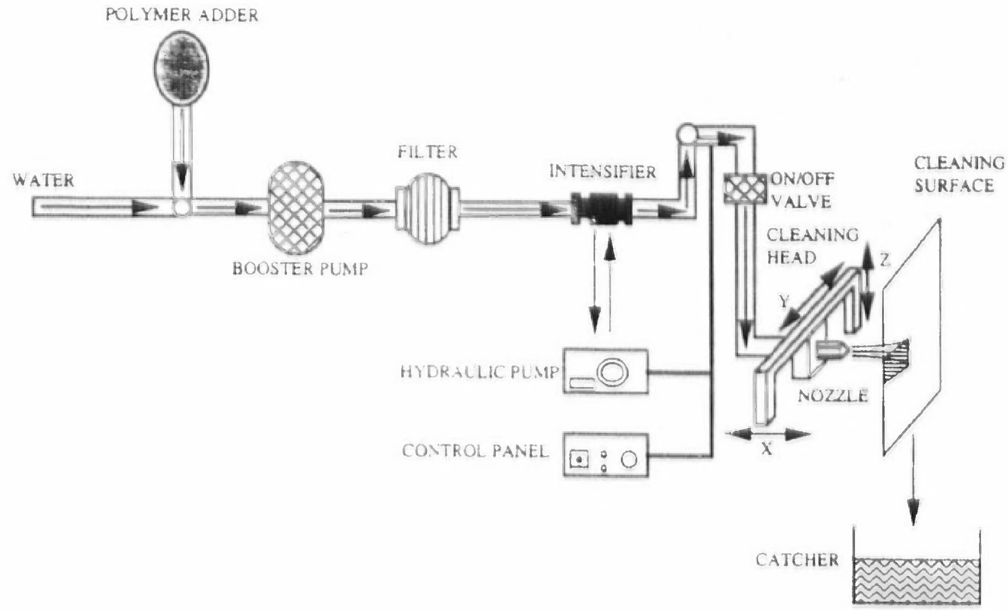

Fig. 5.1 Schematic of waterjet setup.

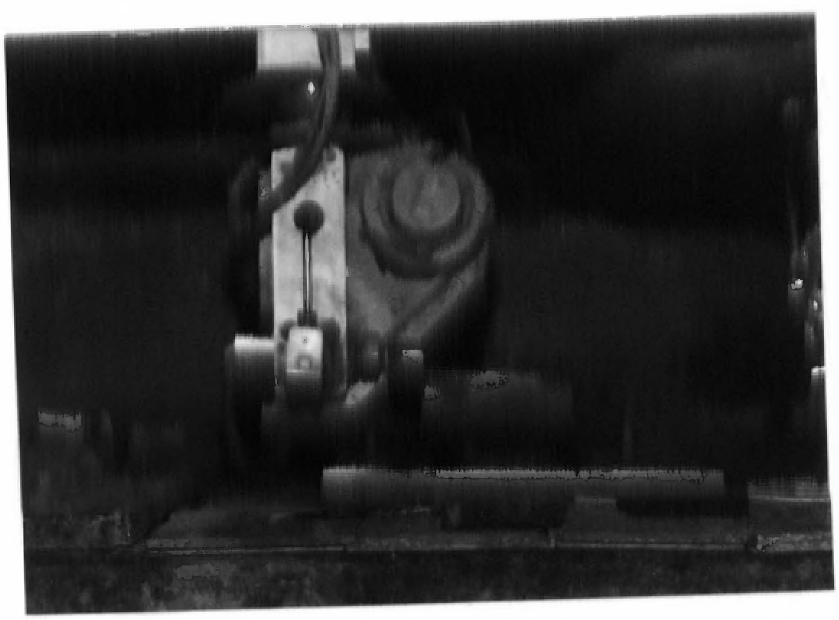

Fig. 5.2 Cleaning head.

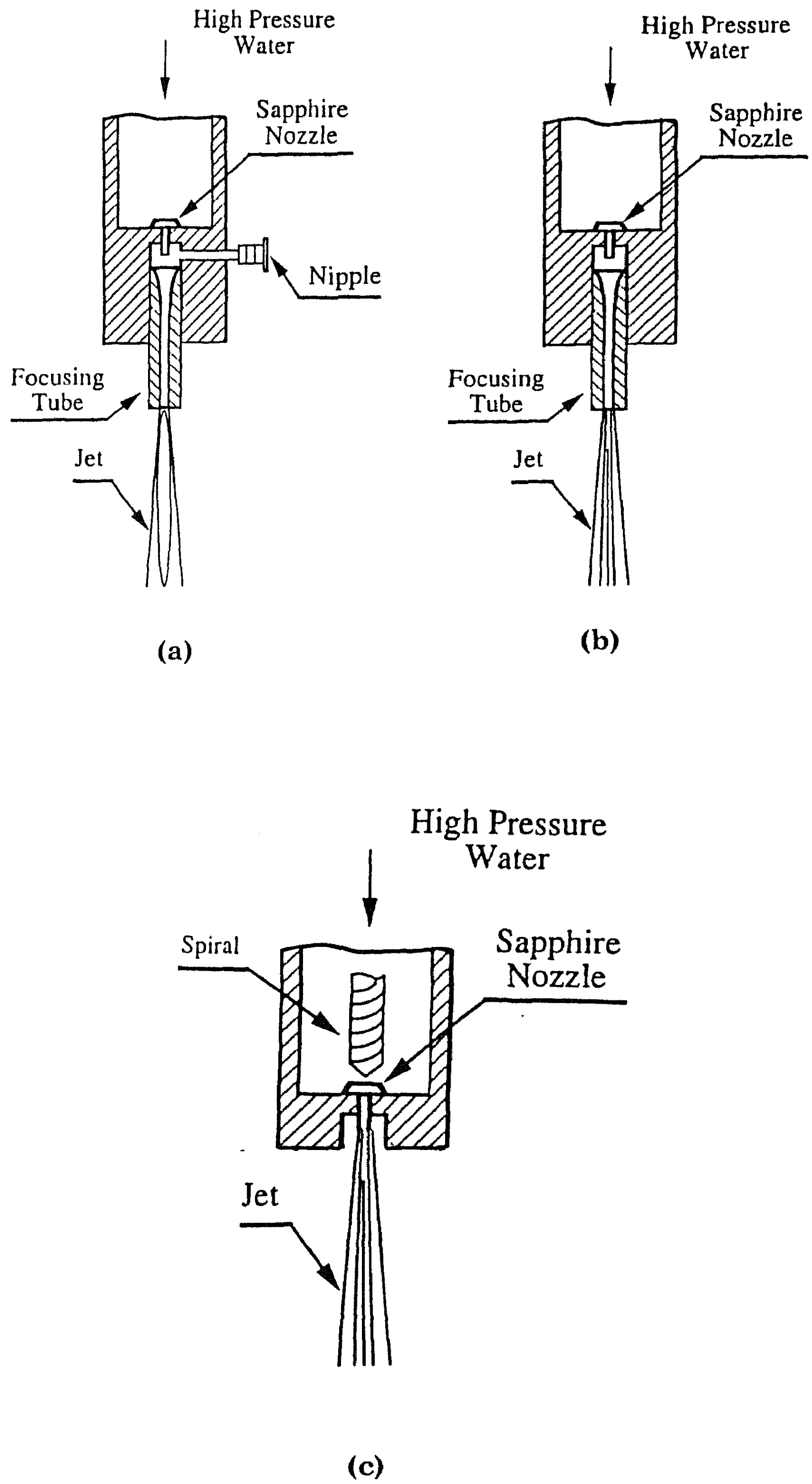

Fig. 5.3 Schematic of (a) conventional, (b) modified, and (c) spiral nozzle bodies.

5.3 Sample Preparation

5.3.1 Substrate

Two types of material, AISI1018 and reactor ceramic (Glass Lined #3008), are selected as substrates for waterjet cleaning or damage tests. AISI1018 is a low carbon steel, and is machined to a block with 4x2x1 in^3. Both surfaces (4x2 in^2) of the block are grinded with sand paper or sand wheel. The Glass Lined #3008 is cut from an actual reactor made by Pfaudler Co. for use.

5.3.2 Coatings

The properties of coatings selected for the experiment study are listed in Table 5.1.

Table 5.1 Application characteristics of coatings

Coating	Color or form	Ingredient	Suitable Substrate	Feature	Make
Oil-Based Paint	Red	Iron Oxide, Petroleum Naphtha, Soya Alkyd Solution, Polyurethane Alkyd Solution, Titanium Dioxide, Calcium Carbonate, TSRN	Wood, Steel, Concrete	Quick Dry, Good Coverage, Easy Brush, Water Resistant, Abrasion Resistant	Paris Paint & Varnish Co., Inc.
Epoxy-Based Paint	Yellow	Epichlorohydrin, bisphenol A, copolymerized, Calcium Carbonate, Polyurethane	Wood, steel, concrete	Strong adhesion, chemical, abrasion resistance, acid, alkali resistance	Krylon Division
Aspirin Deposit	White and Black needle-like Crystals	Film type contaminants (i.e. hydrocarbon and oil based drugs)			Heated after Aspirin Solution Evaporated around 135 C
Rust	Brown				Naturally made by exposure in the air

Details of paints, surface coatings and their properties are discussed by Lambourne, (1987), Taylor and Marks, (1969), and Gaynes, et al., (1967).

5.3.3 Surfactant

A transparent solution of fluorochemical surfactant, FC-722, made by 3M Industrial Chemical Products Division, is used for surface pretreatment of the of epoxy-based paint, and mixed with water in the tank for the waterjet cleaning test. The main contents of this surfactant include Perfluoro Compounds (C5-C18) and Fluoroaliphatic Copolymer.

5.4 Procedure of Sample Preparation

The Reference for coating preparation related to the experiment is taken from the book edited by Gaynes, et al., (1967), and listed in Table 5.2.

Table 5-2 Application characteristics of coatings used in experiments

Generic Type	Resin Composition	Coverage/ Coat (sq. ft/gal)	Dry Time to recoat (h)	Dry Film Thickness per coat (mils)	Outstanding Properties	Suitable Substrate
Drying Oil	Unsaturated drying oil and resin	400 - 450	30 - 40	2 - 2 1/2	Adherence	Wood, steel
Catalyzed Epoxy	Epichlorohydrin, bisphenol A, copolymerized	300 - 400	3 - 5	2 - 3	Adhesion, chemical, acid, hot water resistance	Concrete, wood, steel

Sample of oil-based paint is produced by the use of brush, while the epoxy-based paint is deposited by spray painting. The conditions of coatings preparation are listed in Table 5.3.

Table 5.3 Conditions of coating

Table	Group No.	Coating	Substrate	Painting Method	Time to Dry (h)	Thickness of Coating (mm) *
4-4	1	Oil-based paint	AISI1018	Hand brushing	72	0.09741
4-6	1					
4-8	1					
4-10	1					
4-4	2	Epoxy-based paint	AISI1018	Spraying	48	0.08137
4-6	2					
4-7	1, 2					
4-8	2					
4-9	1, 2					
4-10	2, 3					
4-4	4, 5, 6, 7	Oil-based paint	AISI1018	Hand brushing	72	0.1219
4-6	3, 4, 5, 6					
4-8	3, 4, 5, 6					
4-4	8, 9, 10, 11	Epoxy-based paint	AISI1018	Spraying	48	1.016
4-6	7, 8, 9, 10					
4-8	7, 8, 9, 10					

*Measurement of thickness is described in Chapter 5.5

5.5 Matrix Videometrix Econoscope and Coating Thickness Measurement

The coating thickness of oil-based and epoxy-based paints coated on AISI1018 substrate is measured by the Matrix Videometrix Econoscope shown in Fig. 5.4. The Econoscope uses non-contact techniques to provide rapid dimensional verification of complete parts or specified features of a part. It comprises a general purpose computer (HP-9000 series), a 3-axis positioning control system, a digital image processor and part monitor section.

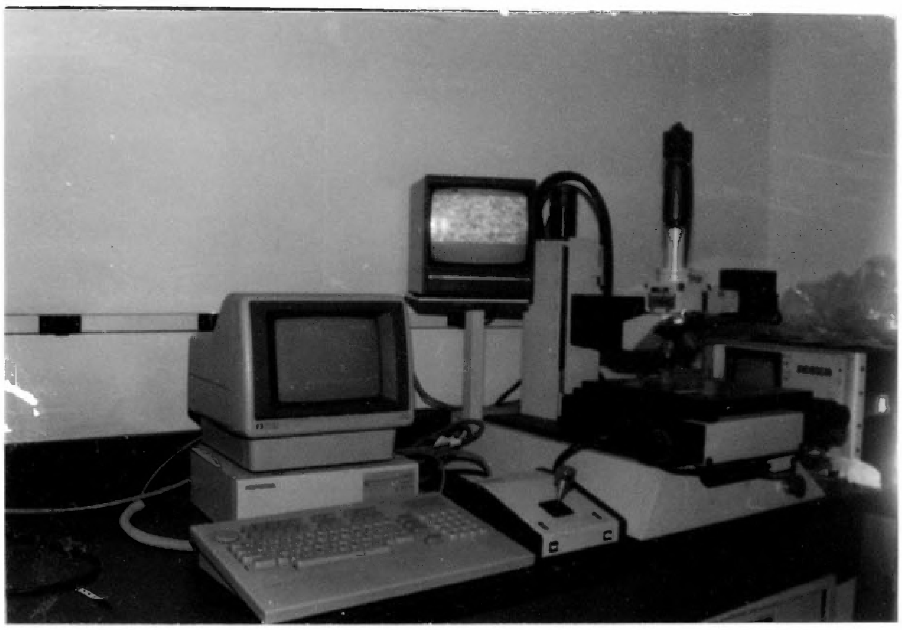

Fig. 5.4 Photo of matrix videometrix econoscope

The software is divided into six major functions. The *Topo* function is used in this study. During measurement, the points to be measured on the coating and substrate surfaces are the distances between the lens and the point by magnification lenses and the light intensity. Measurement of this distance in Z-coordinate can be executed automatically, and the data of the measurement result will be shown on the computer screen. The average thickness of different groups of coating is listed in Table 5.3.

5.6 Procedure of Experiments on Critical Standoff Distance

In all of our cleaning tests, the waterjet stream is perpendicular to the surface of coating material. The sample is located in a sample griper which is put facing the cleaning head. The nozzle body is clamped in the cleaning head, and a sapphire nozzle is inserted inside the nozzle body. A focusing tube which is assembled with the nozzle exit, is also griped in the nozzle body. Three nozzle bodies, conventional, modified, and spiral are used for the test.

The first step in the performance of each group of experiments was identification of the *critical cleaning standoff distance* and the *critical damage standoff distance*. The operational conditions in the course of experiment were selected from the field determined by two critical states. The selected experimental information is presented in Table 4.4 and 4.5.

5.7 Procedure of Experiments on Cleaning Width and Cleaning Rate

Cleaning rate is determined by cleaning width (i.e. strip width) or travel speed, In our experiments, cleaning width was used as an independent variable and the corresponding travel speed is recorded. As the first stage of the experiments, the maximum cleaning width that can be achieved at the conditions in question and the operational parameters which bring about the maximum cleaning width were identified. Using focusing tube, we determined the maximum cleaning width can be attained at the standoff distance equal to 0.65 of the critical cleaning standoff distance (refer to Experiment Groups 4, 6, and 10 in Table 4.8). Thus, experiments were carried out at this optimal value.

For the cleaning width tests of the stationary waterjet without the focusing tube mentioned in Experiment Groups 3 and 7 of Table 4.8, the optimal standoff distance lied at 56.6% of the critical cleaning standoff distance (refer to the theoretical analysis in Chapter 6). While for the cleaning width tests of the moving waterjet without the focusing tube listed in Experiment Groups 5 and 9 of Table 4.8, , the optimal standoff distance lied at 58.8% of the critical standoff distance (refer to the theoretical analysis in Chapter 7). Cleaning width tests for other standoff distances were also made for reference and analysis. The influence of the focusing tube was also tested.

5.8 Coating Material Erosion Test

Erosion tests of two types of coating materials, oil-based paint and epoxy-based paint, were made. During the cleaning process, the intensifier was suddenly turned off which stoped the water stream impact on the coating surface, then the tip of the cleaning path (position where jet stops coating impact), boundary of cleaning width, as well as cleaned surface were observed by microscope and SEM for the study of coating erosion (refer to Table 4.10 in Chapter 4).

5. 9 Measurement and Examination

Cleaning width is measured by dial calipers. Water mass flow rate (GPM) test was measured for four nozzles (no. 14, 12, 10 and 7) at 311 MPa and for nozzle no. 12 at four pressures (311, 207, 138 and 69 MPa). The study of surface topography prior to and after the waterjet cleaning was carried out using the Olympus Optical Microscope with magnification from 7.5 to 64. The camera on the top of the microscope was used to take the picture with fixed the magnification. This microscope was also used to identify the completeness of the deposit removal by the impinging waterjet. The evaluation of the completeness of the cleaning was validated by the use of Scanning Electric Microscope (SEM).

CHAPTER 6

MATHEMATICAL MODELING OF STATIONARY WATERJET CLEANING PROCESS

6.1 General Description

An analytical study of cleaning by stationary waterjets is made. A mathematical model is established to express the cleaning width as a function of standoff distance, water pressure, and nozzle radius based on the waterjet structure and cleaning mechanism. In the cleaning mechanism, removal of material occurs when the impact force generated by the water droplet flow exceeds the coating strength. The maximum cleaning width is shown to exist at a certain standoff distance which has a certain ratio with the critical cleaning standoff distance. The mathematical relations derived are verified experimentally (Chapter 8).

6.2 Structure of Waterjet

Discussions of the structure of waterjet in air can be found in (Yanaida and Ohashi, 1978; Yanaida and Ohashi, 1980; Zou, et al., 1985). Generally speaking, there exist three waterjet regions: the initial, main, and final regions, as illustrated in Fig. 6.1. The initial region is close to the nozzle exit. In this region the instability of the tangential surface separation in the continuous flow stream causes eddies, which bring about an exchange of matter between the water and air. The surrounding air medium is entrained into the water stream and separates the water stream into water particles due to an intensive transverse transfer of mass, momentum, heat, and constituents. Inside the jet there is a wedge-like region known as the potential core, which is surrounded by a mixing layer (Fig. 6.2 shows the photo study of waterjet in air). The velocity inside the core is equal to the jet exit velocity. In the initial region the waterjet can be regarded as a continuous flow having very little air inside the jet. At the end of this region, the effect of air dynamics and continuous interaction of the waterjet with the air medium results in the breakup of the waterjet stream into droplets. This begins the main region. In this region, the mixing of the water stream with air medium continues to the full extent, and the jet stream is disintegrated continuously into droplets due to the entrained air particles. The smaller the distance to the center line of the waterjet stream, the bigger the water droplet size, and the more concentrated the droplet flow. This results in a gradual expansion of the cross section and reduction of the velocity and pressure of waterjet. Between the droplet zone and the surrounding air, there is a mist zone consisting of very fine droplets. The droplets at the boundary of the droplet zone and the mist zone can be considered to have zero velocity. The final region is a diffusion region in which the waterjet is totally broken up into small droplets.

From the investigation of Yanaida and Ohashi (1978) and Zou, et al. (1985), the radius of the jet in the droplet zone, R, is related to the distance from the nozzle exit, x, as follows (refer to Fig. 6.3 for the parameters):

$$R = Cx \tag{6.1}$$

where C is the spreading coefficient. Its value was experimentally observed by Yanaida and Ohashi (1978) to be about 0.03 in the main region and increased to about 0.06 in the

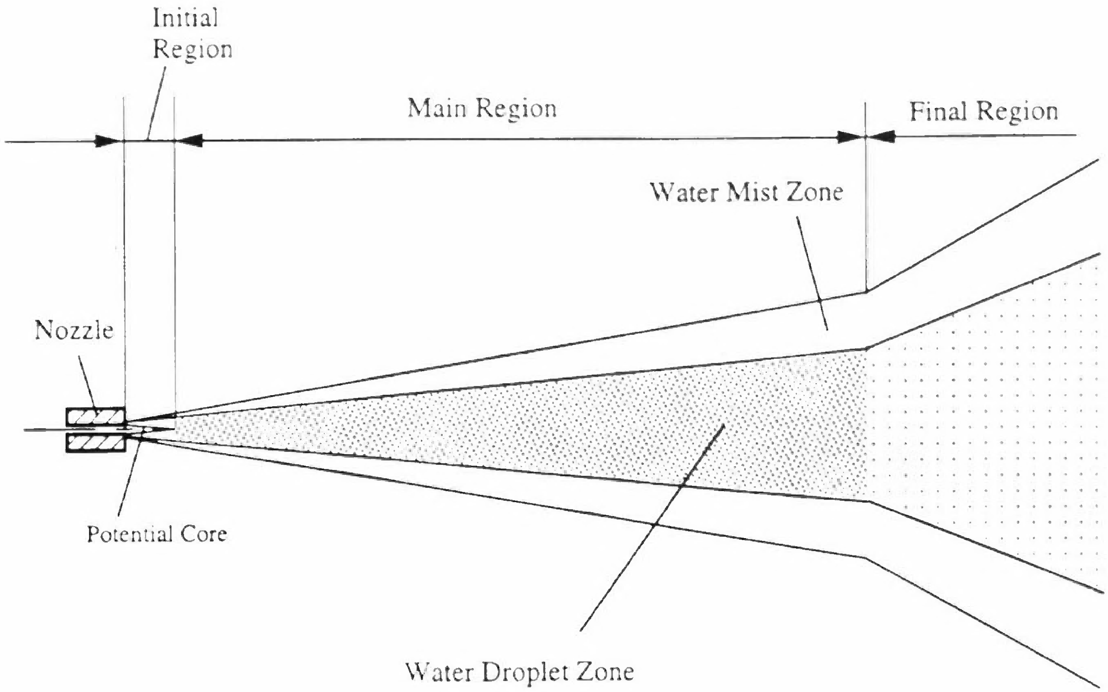

Fig. 6.1 Structure of waterjet in air.

Fig. 6.2 Photo of waterjet in air.

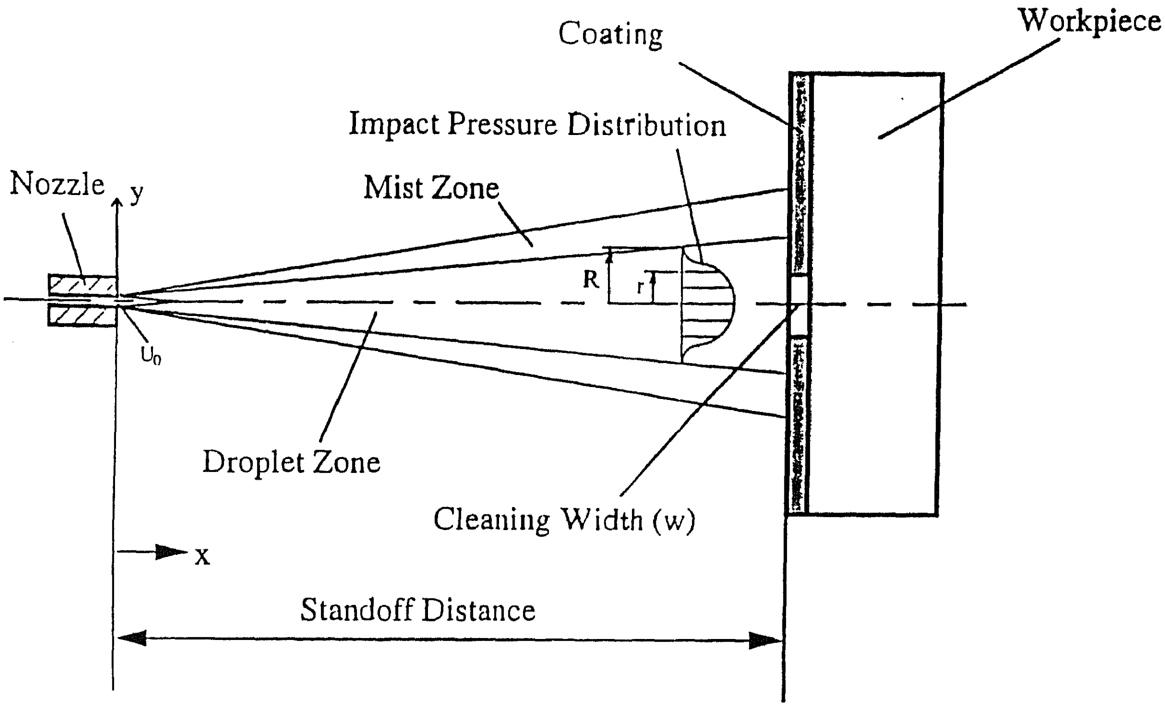

Fig. 6.3 Schematic of waterjet cleaning.

diffusion region. Strictly speaking, C is a function of water pressure and nozzle radius. However, this dependence relationship is highly complex and is not available from the literature. For our present work we will assume C to be independent of water pressure and nozzle radius in the cleaning parameter study, and will show that despite this simplification, the numerical results from our analytical model agree well with experimental results.

According to Erastov's experimental observation (Abramovich, 1963), the mass flow rate in a waterjet has the following relationship

$$\frac{\dot{m}}{\dot{m}_m} = (1 - \xi^{1.5})^3 \tag{6.2}$$

where $\dot{m}$ is the mass flow rate of water droplets per unit area at some point in the flow field, $\dot{m}_m$ is the mass flow rate of water droplets per unit area at the center of the same cross section (in the yz – plane), and ξ is a dimensionless parameter defined by

$$\xi = \frac{\sqrt{y^2 + z^2}}{R} = \frac{r}{R} \tag{6.3}$$

where r is the distance of the point of consideration from the jet center line, and y and z are the y – coordinate and z – coordinate of this point. The jet moves along the z direction. These parameters are depicted in Fig. 6.3.

During the spreading process of the waterjet, the total mass flow rate in each cross section must be equal to the total mass flow rate at the exit of the nozzle. Therefore, the following relation holds:

$$\dot{m}_0 \pi r_0^2 = 2\pi \int_0^R \dot{m} r dr = 2\pi \dot{m}_m \int_0^R \frac{\dot{m}}{\dot{m}_m} r dr \tag{6.4}$$

where $\dot{m}_0$ is the mass flow rate per unit area at the nozzle exit and r_0 is the radius of the nozzle.

Substituting Eqs. (6.2) and (6.3) into Eq. (6.4) results in

$$\dot{m}_m = 5.62 \dot{m}_0 (\frac{r_0^2}{R^2}) \tag{6.5}$$

6.3 Analysis of Cleaning with Stationary Waterjets

Cleaning by stationary waterjets is the process of coating material removal by a waterjet at zero travel speed. Experimental observations have shown that the cleaning width is not as wide as the jet width, and the maximum cleaning width exists in the main region. The variation of cleaning width as a function of standoff distance is influenced by two factors. One is the jet structure. As the waterjet propagates with continuous air entrainment, the jet width grows linearly as the standoff distance increases. The other is the impact pressure. The impact pressure generated by water droplets decreases with increase in the standoff distance. There exists a critical standoff distance at which the coating can not be removed due to the impact pressure becoming too small. The distribution of impact pressure has the shape shown in Fig. 6.3. The impact pressure is the strongest in the middle and decreases to zero at the jet edge. By the influence of these two factors, the maximum cleaning width occurs somewhere between the nozzle exit and the critical cleaning standoff distance. At the critical standoff distance, the jet loses its capability to create enough impact pressure that can exceed the coating strength (Meng, et al., 1996). The impact pressure is not only a function of standoff distance, but is also related to the water pressure and nozzle radius.

Our mathematical model follows the cleaning mechanism that material removal occurs due to the impact of water droplets on the coating material equaling or exceeding a certain strength. The impact pressure at a point in the waterjet is $\dot{m}\psi$, where $\dot{m}$ is the flow rate of water droplets per unit area as discussed before, and ψ is the sound speed in water. There are two strength factors to be considered in the process of cleaning. These are the strength of coating material, S_c, and the adhesive strength between the coating and substrate, S_a. Let S represent the larger of S_c and S_a. Removal of the coating occurs when the impact pressure of the water droplets is greater or equal to the strength S, i.e. cleaning occurs when

$$\dot{m}\psi \geq S \qquad (6.6)$$

6.3.1 Critical Cleaning Standoff Distance

The critical cleaning standoff distance is defined as the distance between the coating surface and the nozzle exit, at which the waterjet has lost its ability to remove the coating material. Theoretically, cleaning at the critical cleaning standoff distance happens at a single point (with zero cleaning width) which is the center of a certain cross section. Thus $\dot{m}_m\psi = S$ at the critical standoff distance. By the use of Eqs. (6.1), (6.5) and (6.6) together with the relationship $\dot{m}_0 = \rho U_0$, where ρ is the water density, it can be shown that the critical cleaning standoff distance, x_c, is related to the cleaning parameters as follows:

$$\frac{U_0 r_0^2}{C^2 x_c^2} = \frac{S}{5.62\rho\psi} \qquad (6.7)$$

The waterjet velocity, U_0, at the nozzle exit is related the water pressure, P, generated by the pump or intensifier as follows:

$$U_0 = k\sqrt{\frac{2P}{\rho}} \qquad (6.8)$$

where k is the coefficient of the waterjet system and is usually around 0.96~0.99. Thus the critical cleaning standoff distance can be expressed as

$$x_c = 2.82(\frac{\psi k}{S})^{0.5}(\frac{r_0}{C})(P\rho)^{0.25} \tag{6.9}$$

6.3.2 Cleaning Width vs. Standoff Distance

If the coating surface is placed somewhere between the nozzle exit and the critical cleaning standoff distance, the cleaning width w satisfies the following equation

$$(1-(\frac{w}{2Cx})^{1.5})^3 \frac{U_0 r_0^2}{C^2 x^2} = \frac{S}{5.62\rho\psi} \tag{6.10}$$

where x is the standoff distance. The above equation can be obtained by using Eqs. (6.1), (6.2), (6.5), and (6.6) and letting $y = \frac{w}{2}$. Substituting Eq. (6.7) into Eq. (6.10) results in

$$w = 2Cx\left[1-(\frac{x}{x_c})^{(\frac{2}{3})}\right]^{(\frac{2}{3})} \tag{6.11}$$

As a check, the cleaning width at the critical cleaning standoff distance is 0, i.e. $w = w_c = 0$, when $x = x_c$, from the above equation.

The maximum cleaning width $w = w_m$ can be obtained by letting $\frac{dw}{dx} = 0$. By differenting Eq. (6.11) with respect to x and letting $x = x_m$, we obtain

$$\frac{x_m}{x_c} = 0.576 \tag{6.12}$$

Substituting Eq. (6.12) back into Eq. (6.11) results in

$$w_m = 0.912Cx_m = 0.525Cx_c \tag{6.13}$$

If the critical cleaning standoff distance x_c is known, the optimal standoff distance x_m can be calculated using Eq. (6.12), and the maximum cleaning width w_m can be calculated from Eq. (6.13).

6.3.3 Effects of Water Pressure and Nozzle Radius on Critical Cleaning Standoff Distance

To investigate the effects of water pressure and nozzle radius on the critical cleaning standoff distance, we start by noting that the maximum impact pressures at the critical cleaning standoff distances of two cleaning processes are the same, i.e. the values of $\dot{m}_m \psi$ are the same. By the use of Eqs. (6.7) and (6.8), we have

$$\frac{P_1^{0.5} r_{01}^2}{C_1^2 x_{c1}^2} = \frac{P_2^{0.5} r_{02}^2}{C_2^2 x_{c2}^2} \tag{6.14}$$

where P_1, P_2, r_{01}, r_{02}, C_1, C_2, x_{c1} and x_{c2} represent the water pressures, nozzle radii, spreading coefficients, and critical standoff distances of the two cleaning processes.

By assuming the spreading coefficient to be constant and thus $C_1 = C_2$, Eq. (6.14) can be rewritten as

$$\frac{x_{c2}}{x_{c1}} = \frac{r_{02}}{r_{01}} \left(\frac{P_2}{P_1}\right)^{0.25} \tag{6.15}$$

With the consideration of the same nozzle radii, i.e. $r_{01} = r_{02}$, Eq. (6.15) becomes

$$\frac{x_{c2}}{x_{c1}} = \left(\frac{P_2}{P_1}\right)^{0.25} \tag{6.16}$$

Also, with the same water pressures, i.e. $P_2 = P_1$, Eq. (6.15) becomes

$$\frac{x_{c2}}{x_{c1}} = \frac{r_{02}}{r_{01}} \tag{6.17}$$

Therefore, we have shown that the critical standoff distance is linearly proportional to the nozzle radius and is proportional to the one-fourth power of water source pressure. It should be noted that these relations are only "approximate" because we have assumed a constant spreading coefficient. Strictly speaking, C is a function of water pressure and nozzle radius as discussed before.

CHAPTER 7

AN ANALYTICAL STUDY OF CLEANING WITH MOVING WATERJETS

7.1 General Review

An analytical study of cleaning by moving waterjets is made. A mathematical model is established using Springer's semi-empirical model of material erosion by liquid impacts. Based on this model, semi-empirical relations are derived to show the cleaning width and critical cleaning standoff distance as functions of various waterjet cleaning parameters, and these relations are verified experimentally (refer to Chapter 8).

7.2 Model of Cleaning with Moving Waterjets

Cleaning by moving waterjets is the process of coating material removal by a waterjet at a certain travel speed. Our experimental observations have shown that the cleaning width is not as wide as the jet diameter and is affected by factors including standoff distance, jet travel speed, water pressure, nozzle diameter, and coating material (Leu, et al., 1994, Geskin, et al., 1995, Meng, et al., 1996a, 1996b). Our observations have also shown that there exists a critical standoff distance, above which jet loses its capability to remove the coating, and that optimal cleaning (with the maximum cleaning width) occurs at a standoff distance somewhere (i.e. between the nozzle exit and the critical cleaning standoff distance). A mathematical model is to be established in this section, and next used to derive relations among the various cleaning variables and compare those from experimental observations.

Our mathematical modeling for waterjet cleaning is based on Springer's erosion model (1976). Springer used a semi-empirical equation to formulate the phenomenon of material erosion by impact of water droplets. The mass loss of the coating material per impact per unit area in his erosion model is proportional to $(\frac{f}{S})^n(\frac{\pi\delta^3}{6})\rho_s$, where f is the impact pressure due to water droplets, S is a parameter representing the material strength, δ is the diameter of the water droplet, ρ_s is the density of the removed material, and n is an empirical constant.

In the moving waterjet cleaning process, the continuous water stream breaks up into a flow of droplets in the main region. As the flow moves across the surface, it delivers a certain amount of water droplets on the surface and removes some coating from the surface. This process is similar to the erosion process described in Springer's model. By using Springer's model, the loss of material mass is related to the impact pressure of the water droplet flow and number of droplets received. The removal of coating material mass per droplet by moving waterjet, β, can be written as follows:

$$\beta = \alpha(\frac{f}{S})^n(\frac{\pi\delta^3}{6})\rho_s \tag{7.1}$$

where α is an empirical constant. The impact pressure due to the water droplet, f, can be expressed as

$$f = \dot{m}\psi \tag{7.2}$$

where $\dot{m}$ is the water mass flow rate per unit area at some point in the flow field as mentioned before, and ψ is the sound speed in the water. The number of water droplets per unit area at a point $(x \;\; y \;\; z)$ for the time interval Δt is (refer to Fig. 7.1)

$$\Delta N = \frac{\dot{m}\Delta t}{\frac{\rho_w \pi \delta^3}{6}} \tag{7.3}$$

where

$$\Delta t = \frac{\Delta z}{V} \tag{7.4}$$

and V is the travel speed of the moving jet. By using Eqs. (7.1), (7.2), (7.3) and (7.4), the coating mass loss per unit area for a fixed y can be obtained as

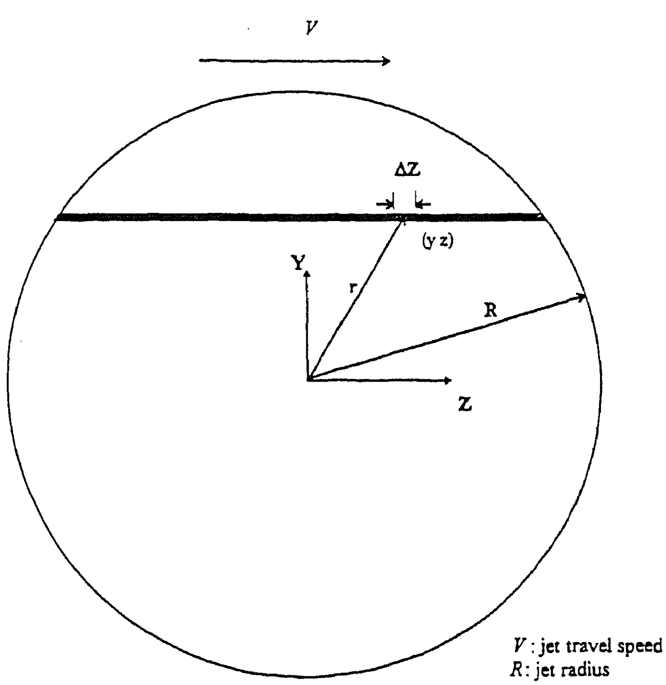

Fig. 7.1 Illustration of moving jet parameters.

$$\eta = \int \beta dN = (\frac{\alpha}{V})(\frac{\rho_s}{\rho_w})(\frac{\psi}{S})^n \int (\dot{m})^{n+1} dz \tag{7.5}$$

where the integration with respect to z is from $-\sqrt{R^2 - y^2}$ to $\sqrt{R^2 - y^2}$. Substituting Eqs. (6.2) and (6.5) into Eq. (7.5) and using $\dot{m}_0 = \rho_w U_0$ lead to

$$= (5.62)^{n+1} (\frac{\alpha\rho_s}{V})(\frac{\psi\rho_w}{S})^n (\frac{r_0}{R})^{2n+2} U_0^{n+1} \int_{-\sqrt{R^2-y^2}}^{\sqrt{R^2-y^2}} \left[1 - (\frac{\sqrt{y^2 + z^2}}{R})^{1.5} \right]^{3n+3} dz \tag{7.6}$$

According to the relation of waterjet velocity at the nozzle exit U_0 to the water pressure P in Eq. (6.8), Eq. (7.6) becomes

$$\eta = (\frac{A}{V})(\frac{r_0}{R})^{2n+2} (P^{0.5n+0.5}) \int_{-\sqrt{R^2-y^2}}^{\sqrt{R^2-y^2}} \left[1 - (\frac{\sqrt{y^2 + z^2}}{R})^{1.5} \right]^{3n+3} dz \tag{7.7}$$

where $A = \alpha (7.95k)^{n+1} (\frac{\psi}{S})^n \rho_s \rho_w^{0.5n-0.5}$.

7.3 Effects of System Parameters on Cleaning

We assume that there is a complete cleaning for an area of concern if the loss of the coating material in terms of mass per unit area is larger than a certain value, η_0. Otherwise, the area is not completely cleaned. Mathematically, complete cleaning is achieved when

$$\eta \geq \eta_0 \tag{7.8}$$

7.3.1 Critical Cleaning Standoff Distance

The critical cleaning standoff distance is defined as the distance between the coating surface and the nozzle exit above which the waterjet is unable to remove the coating material completely at a given travel speed. Theoretically, cleaning at this critical standoff distance results in a line with zero width. Under this situation, $\eta = \eta_0$ at $y = 0$. By the use of Eqs. (6.1) and (7.7), it can be shown that the critical cleaning standoff distance, x_c, is related to the travel speed, V, and other cleaning parameters as follows:

$$x_c^{2n+1} = (\frac{AB}{\eta_0 V})\left(\frac{r_0^{2n+2}}{C^{2n+1}}\right)(P^{0.5n+0.5}) \tag{7.9}$$

where $B = 2\int_0^1 (1-\xi^{1.5})^{3n+3} d\xi$

To investigate the effects of system parameters including travel speed, water pressure and nozzle radius on critical cleaning standoff distance, we note that the coating mass loss per unit area at the critical standoff distance of a cleaning process is always $\eta = \eta_0$ at $y = 0$. Thus, applying Eq. (7.9) to two cleaning processes leads to

$$\left(\frac{x_{c2}}{x_{c1}}\right)^{2n+1} = \left(\frac{r_{02}}{r_{01}}\right)^{2n+2}\left(\frac{C_1}{C_2}\right)^{2n+1}\left(\frac{P_2}{P_1}\right)^{0.5n+0.5}\left(\frac{V_1}{V_2}\right) \tag{7.10}$$

where V_1, V_2, P_1, P_2, r_{01}, r_{02}, C_1, C_2, x_{c1} and x_{c2} represent the waterjet travel speeds, water pressures, nozzle radii, spreading coefficients, and critical standoff distances of the two cleaning processes. By assuming the spreading coefficient to be constant and thus $C_1 = C_2$, Eq. (7.10) becomes

$$\left(\frac{x_{c2}}{x_{c1}}\right)=\left(\frac{r_{02}}{r_{01}}\right)^{\frac{2n+2}{2n+1}}\left(\frac{P_2}{P_1}\right)^{\frac{n+1}{4n+2}}\left(\frac{V_1}{V_2}\right)^{\frac{1}{2n+1}} \tag{7.11}$$

From Eq. (7.11) we have shown the critical cleaning standoff distance variation to the jet travel speed, nozzle radius, and water source pressure. The empirical constant n can be obtained by taking logarithm on both sides of Eq. (7.11) and then performing regression on the ratio of critical standoff distance vs. one or more of the ratios of jet travel speeds, nozzle radii, and water pressures.

7.3.2 Cleaning Width vs. Standoff Distance

If the coating surface is placed somewhere between the nozzle exit and the critical cleaning standoff distance, the cleaning width, w, is such that the material erosion rate per unit area at the edge of this width is the same as that at $y=0$ at the critical cleaning standoff distance. Mathematically, this means that $\eta=\eta_0$ at $y=\frac{w}{2}$ when $R=Cx$. By utilizing Eq. (7.7) and the above relation, we can obtain the relation between cleaning width w and standoff distance x in terms of the following equation:

$$\eta_0=\left(\frac{A}{V}\right)\left(\frac{r_0}{Cx}\right)^{2n+2}P^{0.5n+5}\int_{-\sqrt{(Cx)^2-(\frac{w}{2})^2}}^{\sqrt{(Cx)^2-(\frac{w}{2})^2}}\left[1-\left(\frac{\sqrt{(\frac{w}{2})^2+z^2}}{Cx}\right)^{1.5}\right]^{3n+3}dz \tag{7.12}$$

By using Eq. (7.9), the above equation becomes

$$BC\left(\frac{x^{2n+2}}{x_c^{2n+1}}\right) = \int_{-\sqrt{(Cx)^2-(\frac{w}{2})^2}}^{\sqrt{(Cx)^2-(\frac{w}{2})^2}} \left[1-\left(\frac{\sqrt{(\frac{w}{2})^2+z^2}}{Cx}\right)^{1.5}\right]^{3n+3} dz \qquad (7.13)$$

Since the integrand in Eqs. (7.12) and (7.13) is not integrable, the relation between the cleaning width and standoff distance can not be expressed in a close-form equation. Numerical integration is thus required to obtain the relation between w and x. For $C = 0.0335$ and $n = 2.875$ obtained from our experiments (to be described in Chapter 8.2), the $w - x$ relation is shown in Fig. 7.2. It can be seen that the maximum cleaning width $w = w_m$ exists when $x = x_m = 0.588x_c$.

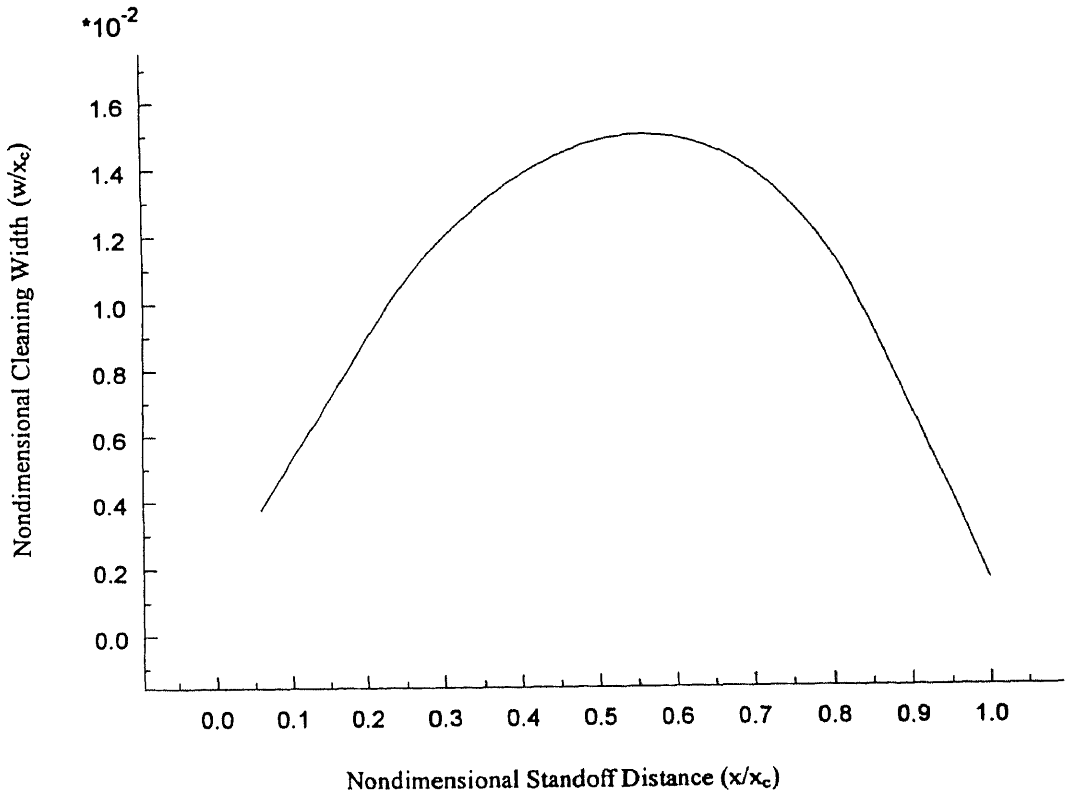

Fig. 7.2 Cleaning width vs. standoff distance, both dimensionalized with respect to critical cleaning standoff distance.

CHAPTER 8

RESULTS AND DISCUSSION

8.1 Waterjet Coating Removal

Experimental investigation of waterjet removal of various coatings was carried out. The experimental results of the removal of rust, aspirin deposit, oil, and epoxy based paint by waterjets are shown in Figs. A.1, A.2, and A.56. These photos indicate that high speed waterjet cleaning is a practical technology which can be successfully used for the removal of various coatings and deposits. Development of this technology can be used to substitute the traditional chemical based cleaning.

8.2 Experimental Verification of Analytical Results

The relationships of cleaning width with standoff distance, critical standoff distance with water pressures and nozzle diameter enable us to predict cleaning width and optimal cleaning standoff distance only using one empirical data, the critical cleaning standoff distance for a given condition. These developed relations are based on the commonly acceptable anatomy of turbulent water jet submerged in the air. The constructed equations contain one empirical coefficient, the waterjet spreading coefficient, which was determined using the equation of linear regression between the radius of the jet and standoff distance (Eq. 6.1). Obtained value of the jet spreading coefficient, 0.0335, complies with literature data. Another empirical constant, n, is 2.875, which is obtained from regression analysis of the measured critical standoff distance vs. jet travel speed. The analytical results shown below for the stationary jet is using the data measured at 311 MPa with nozzle no. 14 for the removal of each type of paint, while for the moving jet, the data is measured at 138 MPa and 10.16 m/min. with nozzle no. 10 for each type of paint removal. A good agreement between analytical and experimental results for the stationary and moving waterjet cleaning processes was found.

8.3 Analysis of Critical Standoff Distance and Effective Working Space

It has been observed in the course of experimental studies that there exist two critical standoff distances: *Critical Cleaning Standoff Distance* and *Critical Damage Standoff Distance*.

8.3.1 Cleaning at the Critical Cleaning Standoff Distance

Figures A.3 shows typical paint removal at the critical standoff distance by stationary and moving jets. It can be noticed that the cleaning width and a small spot at this condition is minimal. Beyond this critical standoff distance, cleaning becomes ineffective and no clearly identified decoated region is observed. These peculiarities of the jet behavior are due to the pattern of energy dissipation in a turbulent jet which is well understood and documented. Waterjet energy gradually decays with the increase of the standoff distance, and only when the effective jet energy is greater than or equal to the larger one of the adhesive strength or coating strength, coating can be removed.

8.3.2 Cleaning at the Critical Damage Standoff Distance

Figures A.4 shows the surface damage and erosion of the Glass Lined #3008 substrate impinged by a moving jet. Although the yield strength of the substrate material in waterjet cleaning is usually much higher than that of the coating material, the energy of the waterjet may be sufficient to cause damage on the substrate surface if the surface is very close to the jet exit. This standoff distance is below the critical damage standoff distance. There is no substrate surface erosion occurring beyond this critical cleaning standoff distance.

8.3.3 Effective Working Space

The effective working space for waterjet cleaning should be a region between the critical cleaning standoff distance for coating removal and the critical damage standoff distance for free of substrate damage processing. A substrate surface of AISI1018 prior to a jet impingement is shown in Fig. A.5, and the same surface after waterjet paint removal in the effective working space is shown in Fig. A.6. There is no coating left and also no damage found.

8.3.4 Analyses of the Critical Cleaning and Damage Standoff Distance

Experimental studies of the critical cleaning and damage standoff distances using focusing tube are based on Group No. 1, 2 and 3 of Experiment in Table 4.4, and Table 4.5. The experimental results are shown in Figs. A.7 to A.22 (Appendix A).

It can be observed that the critical standoff distance is influenced by the diameter of the focusing tube, and for the same size of the sapphire nozzle, larger diameter of the focusing tube yields a greater critical standoff distance, and a greater critical standoff distance is obtained with a larger sapphire nozzle diameter due to the higher energy content of the jet. These two standoff distances also increase with increased in water pressure because more energy is delivered by the waterjet at the sample surface. Commercial nozzle body assures a larger critical standoff distance than that of the modified nozzle body at the same size of the nozzle from the experimental results. Compared with the results of the other two nozzle bodies at the same water pressure, the spiral nozzle body yields the shortest critical cleaning standoff distance. This phenomenon is due to widening the jet by the screw located prior to the orifice and transferring certain energy across the jet from the moving direction. A larger critical cleaning standoff distance was received for the epoxy-based paint removal from the substrate of the Glass Lined #3008 than that of the same coating removal from the substrate of AISI1018 at the same operation conditions. The obvious reason for this phenomena is a weaker adhesive strength between the coating and the smooth surface of the Glass Lined #3008 than that between the coating and substrate surface of AISI1018 steel.

From the figures discussed above, it is clear to see that the critical cleaning and damage standoff distance decreases with the increase of the travel speed. The increase of the travel speed results in less energy delivered per unit area of the coating surface (less number of the droplets impact), so the standoff distance needs to be reduced (droplet velocity increase with the reduction of the standoff distance) to compensate for the reduction of droplets.

8.3.5 Experimental Verification of Analytical Results

A series of systematic experimental investigations of the coating removal by stationary and moving waterjets without the use of focusing tubes were carried out to verify the analytical results. Also a comparison of coating removal using the modified nozzle body with and without a focusing tube at otherwise same operating conditions was made. Experiments are based on Group No. 4-11 of Experiment in Table 4.4. The experimental results are shown in Figs. A.23 to A.52 and A.140 (Appendix A).

Theoretical analysis and experimental studies prove that the critical cleaning standoff distance increases as the water pressure and nozzle number increases for the stationary and moving jet cleaning processes, because more energy is delivered with the increase in the water pressure and nozzle number. Also, the critical cleaning standoff distance decreases when the travel speed increases for the moving jet cleaning process. The experimental data show that with focusing tubes no. 93 and 63, critical cleaning standoff distance increases compared to testing without using a focusing tube but not significantly. Optimal cleaning standoff distance follows the theoretical investigation, which constitutes 0.576 of the critical cleaning standoff distance for the stationary jet, and 0.588 of the critical cleaning standoff distance for the moving jet. All the analytical and experimental results agree fairly well.

8.3.6 Effect of Surfactant Pretreatment

Figure A.53 shows the comparison between epoxy-based paint removal with and without surfactant FC-722 coating sample pretreatment at the otherwise same operating conditions, i.e. modified nozzle body, sapphire nozzle no. 14, focusing tube no. 63, 172 MPa water pressure, and travel speed of 10.16 m/min. The duration of surfactant pretreatment is 2 minutes. It is found that the cleaning width with surfactant pretreatment is much wider than that without surface pretreatment. Using surfactant like FC-722 can be helpful in increasing the critical cleaning standoff distance because the reaction of the surfactant to the coating may weaken the adhesive strength between the coating and substrate or strength of the coating itself.

8.4 Investigation of Geometry and Productivity of Cleaning

Cleaning rate is a linear function of cleaning width and travel speed. Cleaning width is related to jet structure and impact conditions, and decreases with the increase of travel speed. The admissible standoff distance maximizes the cleaning width for a stationary jet, and rate of cleaning at a given travel speed for a moving jet. The theoretical prediction was substantiated experimentally.

8.4.1 Cleaning Width

Figure A.54 shows the correlation between cleaning width and the standoff distance for stationary and moving jet cleaning in photo, which clearly identifies the existence of the extremism at this correlation. By the use of a focusing tube, maximum cleaning width was attained at 0.67 times the critical cleaning standoff distance at a water pressure of 138 MPa, while it was 0.63 times the critical cleaning standoff distance at a water pressure of 69 MPa. These results are shown in Fig. A.55. The experimental studies with using focusing tube were carried out at optimal cleaning standoff distance which was assumed to be equal to 0.65 of the critical cleaning standoff distance.

Figure A.56 shows that the cleaning width can be significantly increased by the improvement of the conditions of the jet formation. The use of the spiral nozzle body had a strong effect on the deposit removal. A screw inserted in the nozzle body in front of the sapphire nozzle substantially increases the cleaning width, which evidently demonstrates the potential of the enhancement of the deposit removal by the improvement of the jet anatomy. One of the most effective means of such an improvement is optimization of the nozzle body design.

8.4.2 Investigation of Surfactant Influence on Cleaning Width

A 1% solution of fluorochemical surfactant FC-722 is applied to an epoxy-based paint on a substrate of AISI1018 for duration ranging between 2 minutes and 24 hours, the paint is then removed by the moving jet at 172 MPa. The correlation between the cleaning width and the duration of surfactant pretreatment is shown in Fig. A.53, which clearly indicates that coating surface pretreatment by the FC-722 solution leads to a larger cleaning width and hence an increased cleaning rate. When the duration of the fluorochemical solution treatment was for two minutes, the cleaning width increases as much as 2.5 times compared to without surfactant pretreatment. However, further increase of the pretreatment duration has no practical effect on the cleaning width. Figure A.57 shows the effect of the surfactant FC-722 pretreatment on the cleaning result. The effectiveness of such a pretreatment is clearly demonstrated. Also shown in Fig. A.53 is result of comparison of surfactant FC-722 premixed with and without mixing source water in tank. There is no obvious cleaning width increase for the both cases.

8.4.3 Experimental Verification of the Analytical Results

Experiments of the investigation of cleaning width enable us to verify the analytical results obtained in Chapters 6 and 7. The results based on Table 4.8 are shown in Figs. A.58 to A. 97 and A.141 (Appendix A).

Cleaning width is proved theoretically and experimentally to increase as standoff distance increases until the maximum cleaning width is obtained. After that, cleaning width decreases as the standoff increases until to zero. Increased water pressure and nozzle number, which delivers more energy, results in the increase of the critical cleaning standoff distance, and thus cleaning width. Maximum cleaning width occurs at 0.576 times of the critical cleaning standoff distance for the case of the stationary jet cleaning, and at 0.588 times of the critical cleaning standoff distance for the case of the moving jet cleaning. Also, the maximum cleaning width decreases as travel speed increases due to less energy received per unit area of coating. An agreement between the analytical and experimental results is obtained for all presented cases.

8.4.4 Analysis of Cleaning Rate

Calculation of the cleaning rate is the maximum cleaning width multiplied by the corresponding travel speed. Shown in Figs. A.98 to A.118 (Appendix A) are the experimental data, as well as experimental verification of the analytical results for the moving jet removal of oil-based and epoxy-based paint for various operating conditions with and without the use of focusing tubes. Selected numerical data are given in Tables A.1 and A.2.

For the concern of the travel speed range, it is clearly shown in these figures that the cleaning rate increases with increased travel speed, water pressure for the cases using or without using focusing tubes, and also nozzle number for the cases without using focusing tube. It is easier to remove oil-based paint than epoxy-based paint as expected. Spiral nozzle jet, which is modified by inserting a screw in the nozzle body, leads to increased jet width and also increased the cleaning width.

It has to be mentioned that for the concerned range of the travel speed, the cleaning rate still increases as the travel speed increases although the cleaning width decreases as the travel speed increases. This can be explained by the influence of the cleaning width reduction on the cleaning rate due to the increase of travel speed is being smaller than that of travel speed increase on the cleaning rate.

8.5 Investigation of Water Consumption

Water consumption is an important criterion of the evaluation of the waterjet cleaning technology. This parameter is determined by the rate of cleaning and water flow.

8.5.1 Water Flow Rate

Water flow rate is measured at various process conditions for the evaluation of water consumption in experimental Groups 1 and 2 (refer to Tables 4.8). The results of the measurement are shown in Table A.3, compiled with data suggested by Flow Inc. (Table A.4).

8.5.2 Analysis of Water Consumption

The information concerning water consumption and experimental verification of the analytical prediction are shown in Figs. A.119 to A.139 (Appendix A).

The acquired data shows that minimal water consumption is attained with the use of the spiral nozzle body. It has been shown that water consumption decreases with the increase of travel speed or cleaning rate as well. Water consumption is almost the same for different pressures, and decreases a little bit as water pressure increases, due to the fact that the cleaning width increases as water pressure increases, but not as much in proportion to water flow rate increases. Also, water consumption decreases with the decreases in nozzle diameter because the water flow rate decreases in proportion much more than the cleaning width decreases as the nozzle size decreases. The experimental data also complies very well with the theoretical prediction.

8.6 Investigation of Coating Erosion by Impingement of the Waterjet

Oil-based and epoxy-based paint erosion by waterjet impingement was experimentally investigated. Micrograph of Fig. A.142 shows oil-based paint erosion in the front of the moving jet. It can be clearly observed that there are cracks, tears and lifting at the coating/substrate boundary. Shown in Fig. A.143 is the epoxy-based paint removal. Plastic deformation is found at the coating/substrate boundary.

The oil-based paint belongs to elastic coating materials, and its adhesion strength is comparatively small. There are two feasible mechanisms for removal of this paint by the impinging waterjet. The paint can be destroyed by the later water flow from the impingement zone. The flow enhances cracks developed in the coating due to impact . This results in the lifting and tearing of the coating. Another mechanism involves the droplets erosion of the deposit which eventually results in the paint tear. We suggest that both mechanisms take place in the course of removal of the oil paint.

Microscopic study of the typical epoxy-based paint identifies mussel-like pits which are believed to be caused by the droplets impingement. This kind of coating is more brittle, and the adhesion strength is very strong. There are no cracks, lifting or tearing found at the jet boundary during the removal of this paint We suggest that the removal of the epoxy based paint is due to the droplets erosion.

Micrograph of Fig. A.144 shows at the jet boundary during the removal of the epoxy paint pretreated by the surfactant FC-722. It can be observed that cracks are developed at the rather smooth jet. The change of mechanism of the decoating (crack vs. erosion) is probably due to the change of paint properties in the course of the pretreatment.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Experimental and theoretical studies have been carried out to investigate the precision cleaning of steel and glass surfaces using high-pressure, low-volume waterjets. Deposit removal by stationary and moving jets under a wide range of operational conditions was investigated experimentally. The theory of turbulent jets was used to develop a theoretical description of the deposit removal. A good agreement between the theoretical prediction and experimental results was attained. The following conclusions are drawn as the results of the performed research:

1. It is demonstrated that a generic precision cleaning technology can be created by the use of a high-pressure waterjet. The feasibility of the replacement of chemical cleansers currently used for precision cleaning of various parts by-high pressure low-volume waterjet is shown.
2. The conditions of jet formation and impingement which assure reduction of the deposit amount down to an acceptable level, are readily attainable. No special condition for precision cleaning using the high speed waterjets is needed. High speed jet cleaning is much less expensive than the traditional chemical cleaning. Most important, this technology is environmentally benign and meets the existing and pending environmental regulations.

3. Two critical standoff distances, the *critical cleaning standoff distance* and the *critical damage standoff distance* are used to identify the *effective working space* for a given process condition (travel speed, nozzle design, water pressure). The effective working space assures desired deposit removal without substrate damage.
4. A mathematical description of deposit removal by stationary and moving waterjets was pioneered using the conventional model of turbulent jets. Theoretical predictions were validated by the acquired experimental data. This demonstrates the feasibility of using the existing theory of turbulent jets for description of a high speed stream of water droplets in air.
5. Equations for the prediction of the critical cleaning standoff distance and cleaning width are constructed. Besides readily available information (traverse speed, water pressure, nozzle diameter) and constants determined in this study, the developed equation contains only one empirical number, the critical cleaning standoff distance, for the prediction under a given process condition.
6. Equations determining the optimal standoff distance for cleaning by moving and stationary waterjets were derived. The optimal standoff distance constitutes 0.6-0.7 of the critical cleaning standoff distance.
7. Cleaning width and thus productivity can be substantially increased by the improvement of the condition of jet formation. The *spiral* nozzle body developed in this work significantly increases process productivity and reduces water consumption.
8. Deposition of the surfactant EC-722 for a short duration (2 minutes) prior to water impact increases cleaning width significantly.

9. Analysis of micrographs of the boundary between the impingement zone and the remaining coating shows existence of two mechanisms of the deposit removal by the impinging jets. The lateral jets generated in the impingement zone bring about peeling of the deposit already weakened by cracks which are developed due to the impact stresses. Deposits can also be eroded by impacting droplets. It is suggested that the combination of these two mechanisms brings about surface cleaning.
10. The result of the experimental study and theoretical analysis provides an adequate database for design of commercial cleaning systems.

9.2 Recommendations

For the future work we recommend:

1. To design practical water based systems for precision cleaning of components and equipment, which eliminate the use of solvents for cleaning in chemical and pharmaceutical reactors.
2. To use the methods of fracture mechanics to develop a theoretical model of deposit destruction by the impinging jets.
3. To Integrate the theory of jet development and deposit destruction to result in the creation of a comprehensive theory of waterjet cleaning.
4. To Integrate the theory of waterjet cleaning and nozzle guidance to result in the development of the comprehensive knowledge base of cleaning.
5. To consider a practical implementation of the environmentally benign cleaning technology as an urgent and achievable task.

APPENDIX A

EXPERIMENTAL AND ANALYTICAL RESULTS OF WATERJET CLEANING

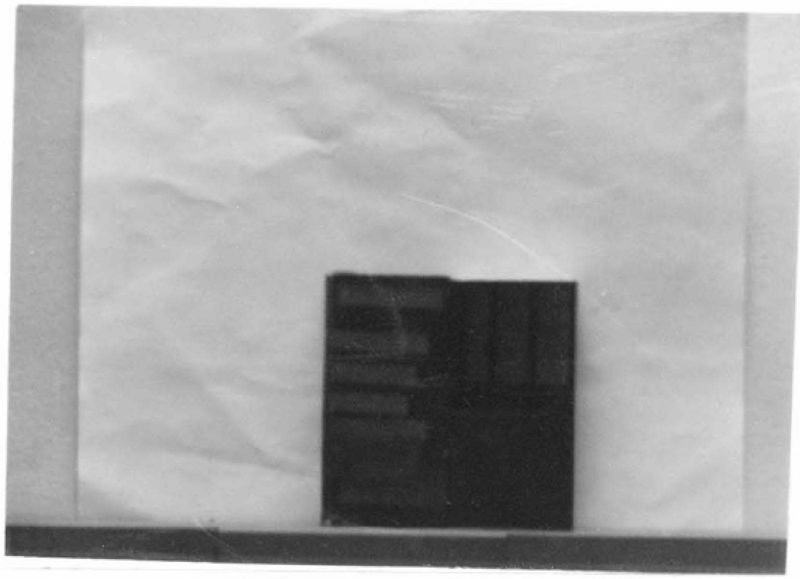

Fig. A.1 Rust removal by waterjet.

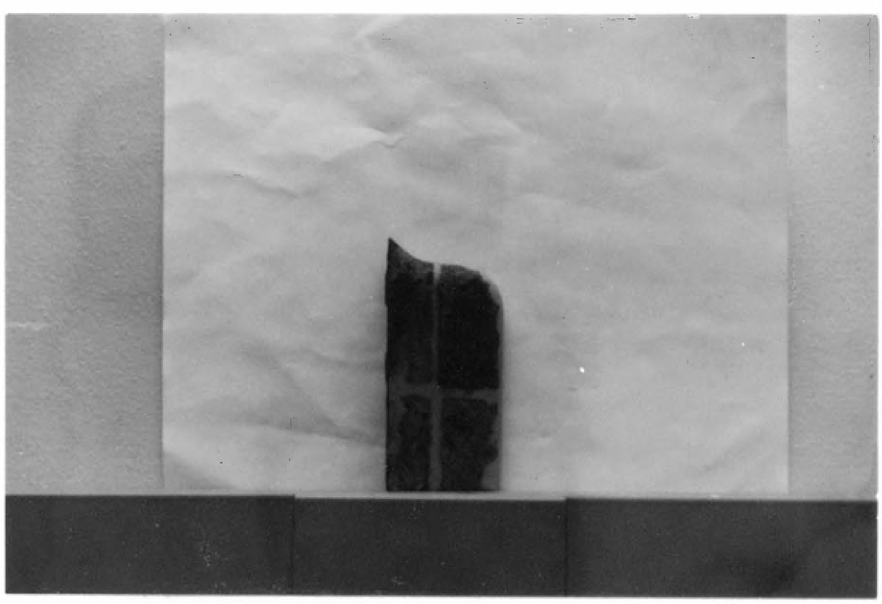

Fig. A.2 Aspirin deposit removal by waterjet.

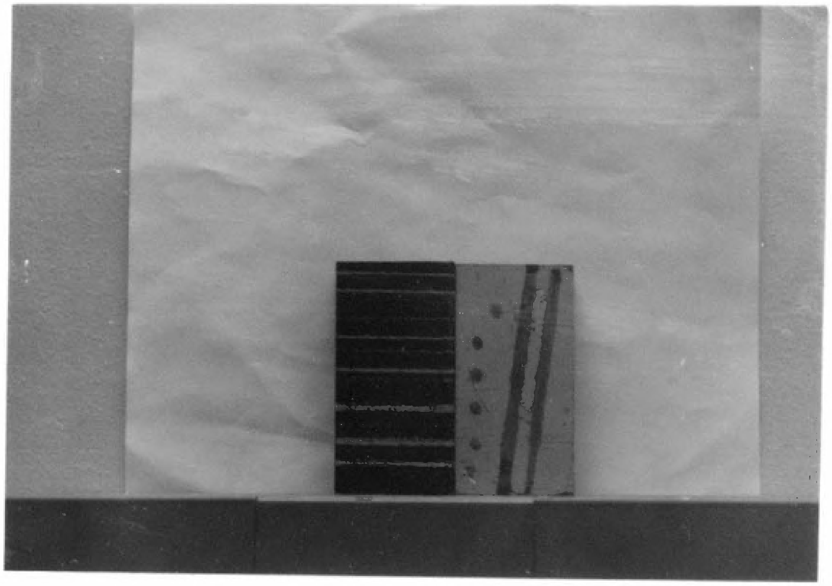

Fig. A.3 Cleaning by waterjet at the critical cleaning standoff distance (the small spot at the right side of the right sample was made by stationary jet, the very narrow line on the left sample was made by moving jet).

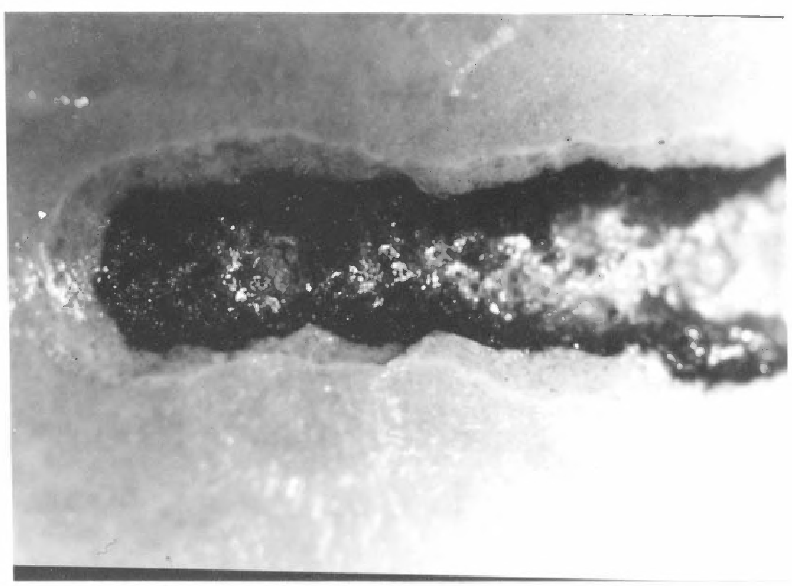

Fig. A.4 Surface of Glass Lined #3008 damaged by waterjet.

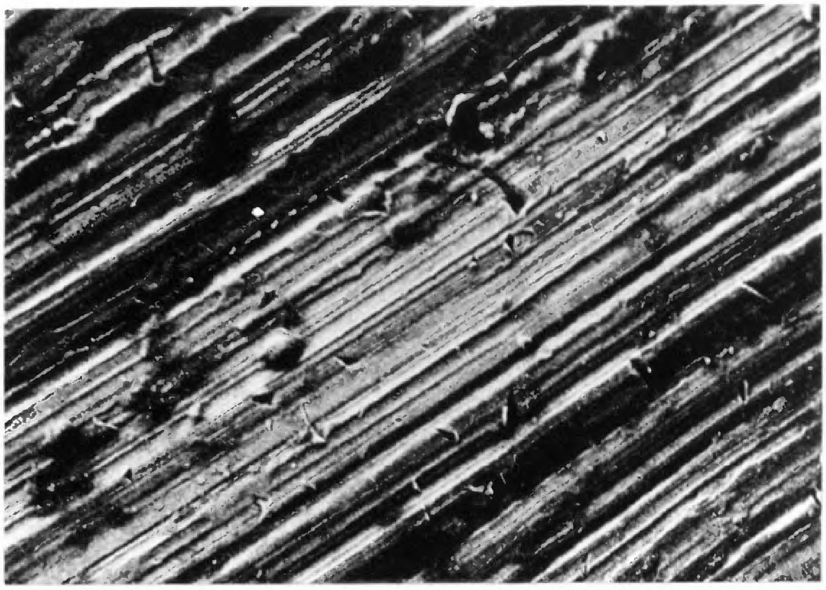

Fig. A.5 Substrate surface of AISI1018 prior to a jet impingement.

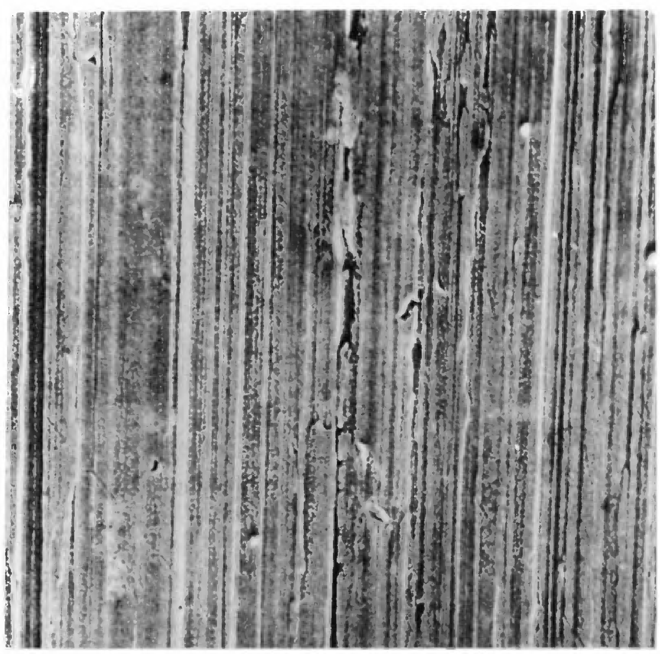

Fig. A.6 Substrate surface of AISI1018 after a jet impingement (no coating left and no damage found).

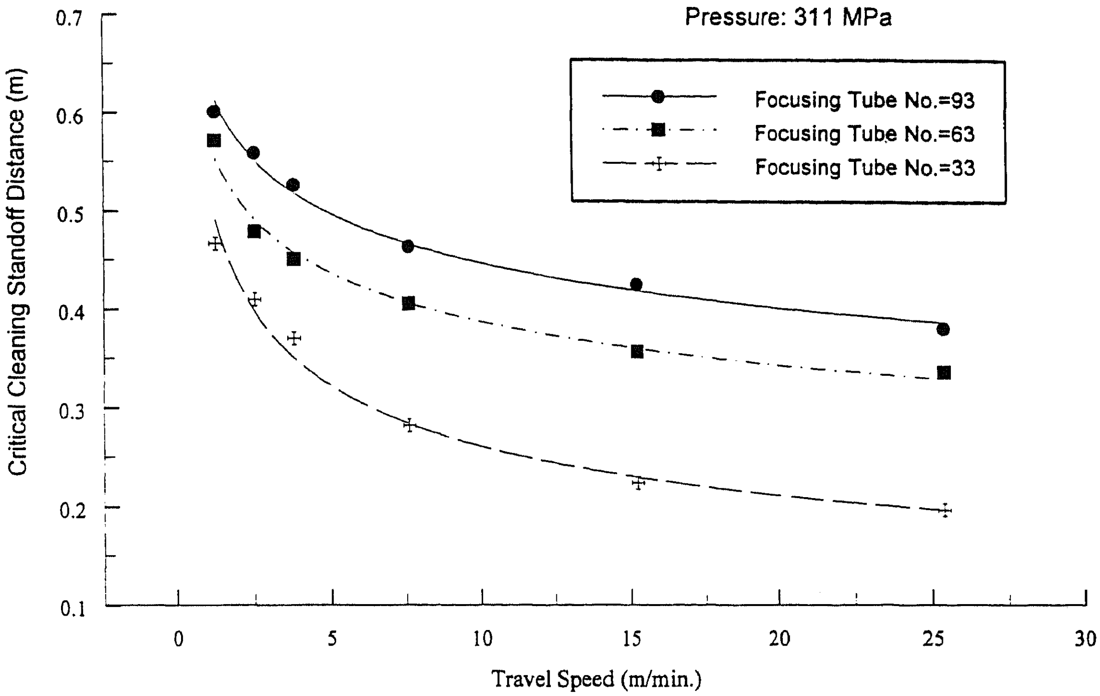

Fig. A.7 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 14 and three focusing tubes at 311 MPa.

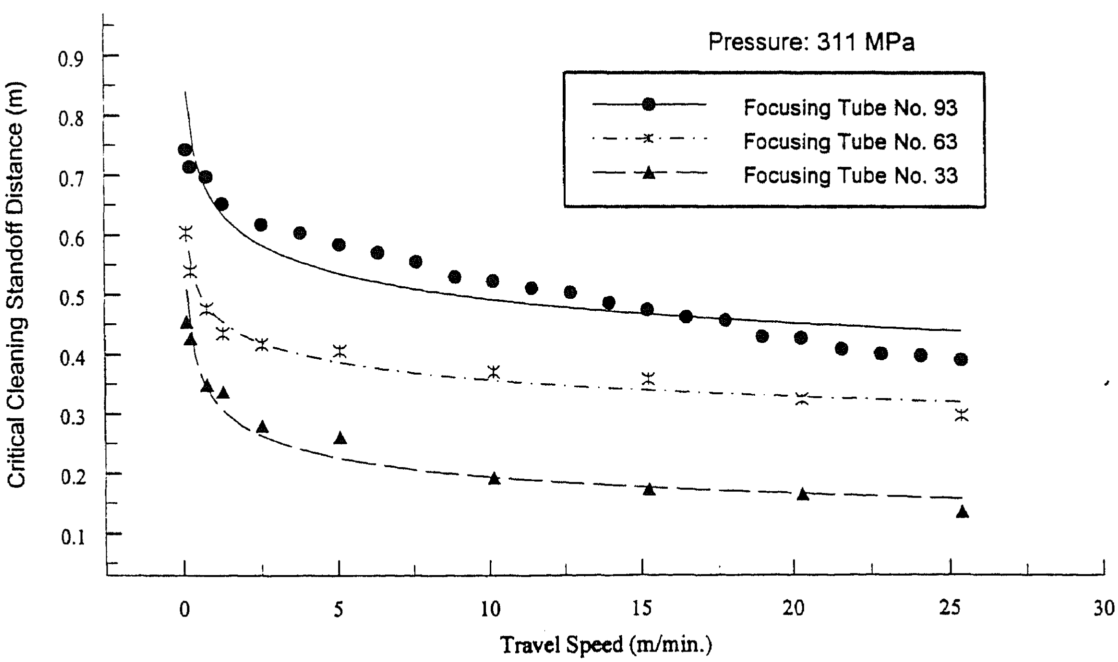

Fig. A.8 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 12 and three focusing tubes at 311 MPa.

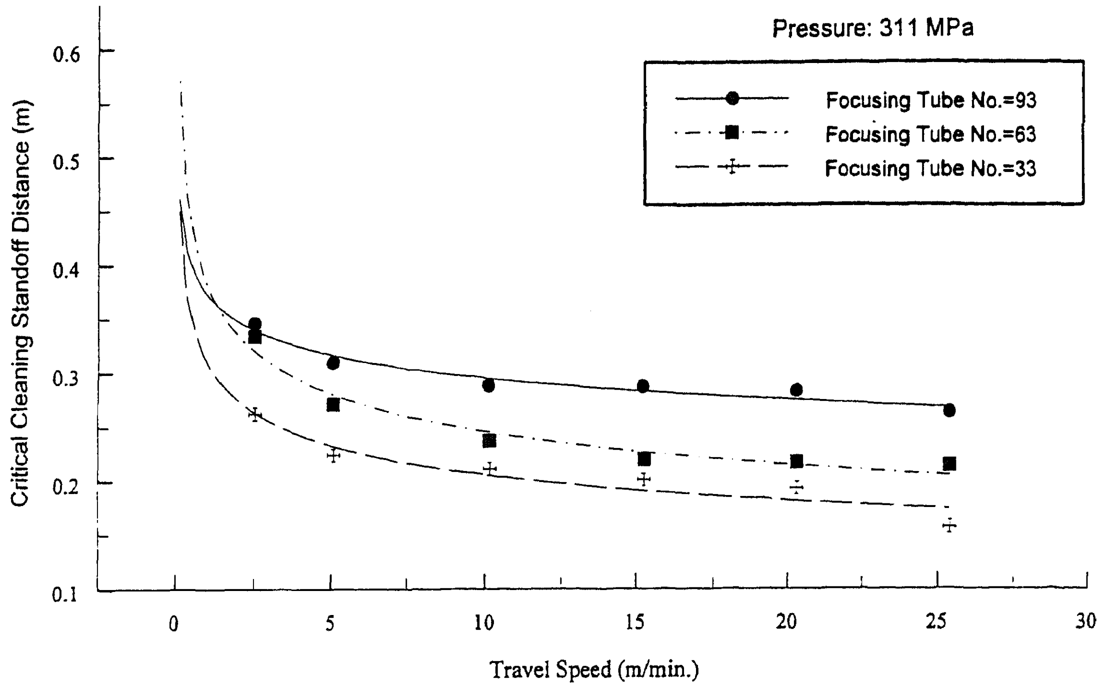

Fig. A.9 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 7 and three focusing tubes at 311 MPa.

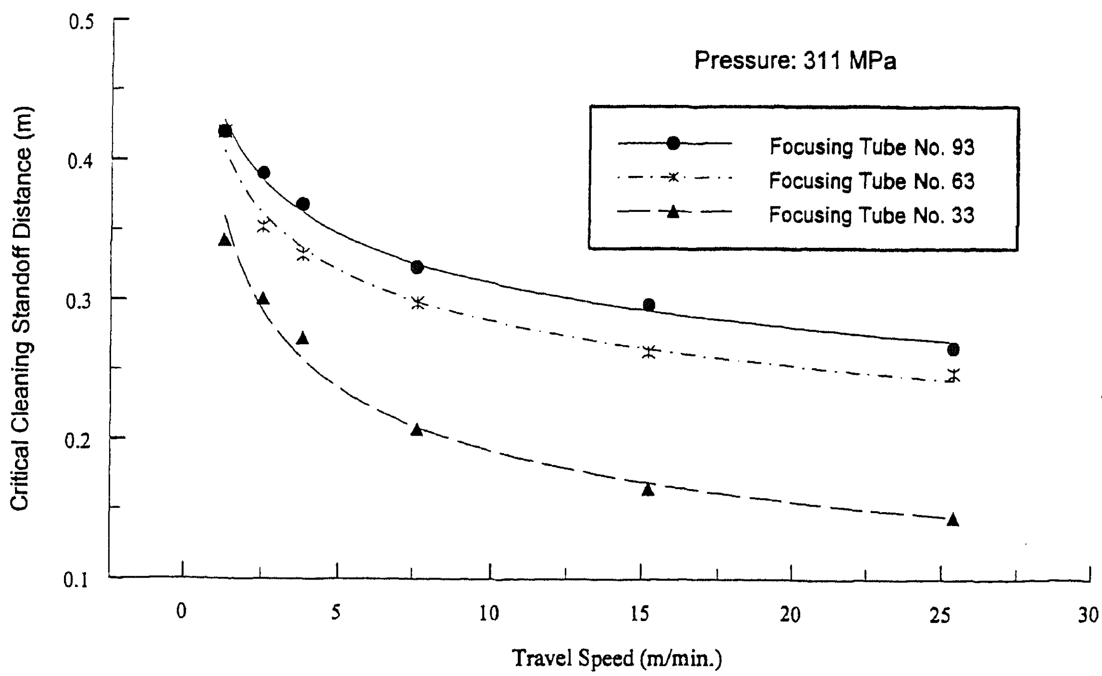

Fig. A.10 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 14 and three focusing tubes at 311 MPa.

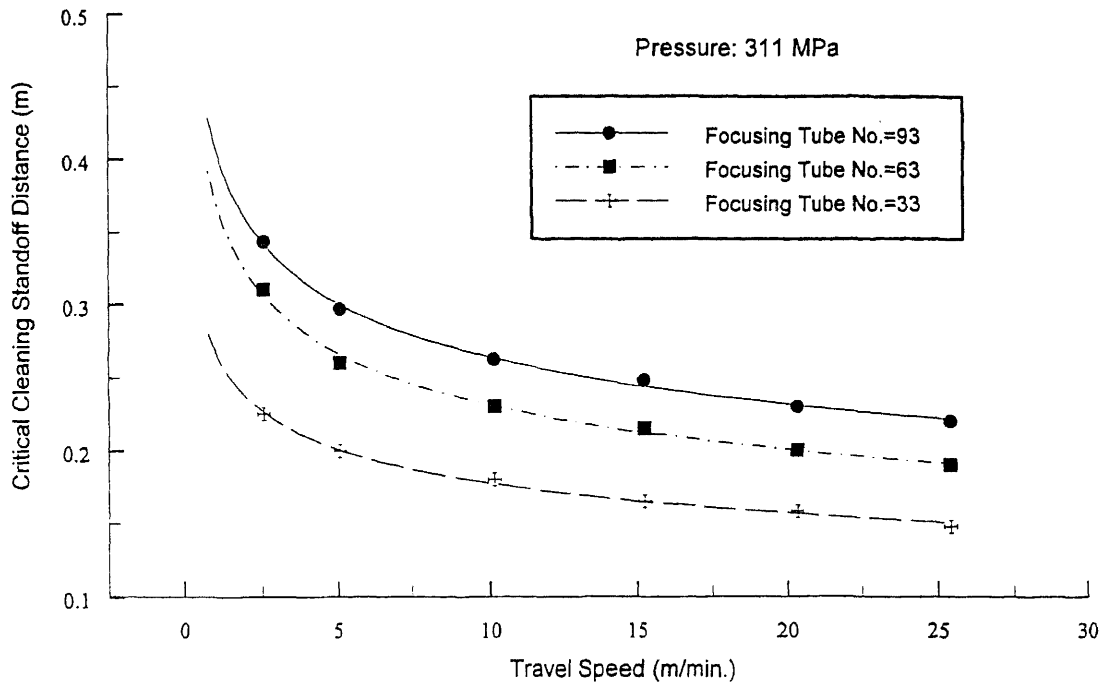

Fig. A.11 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 12 and three focusing tubes at 311 MPa.

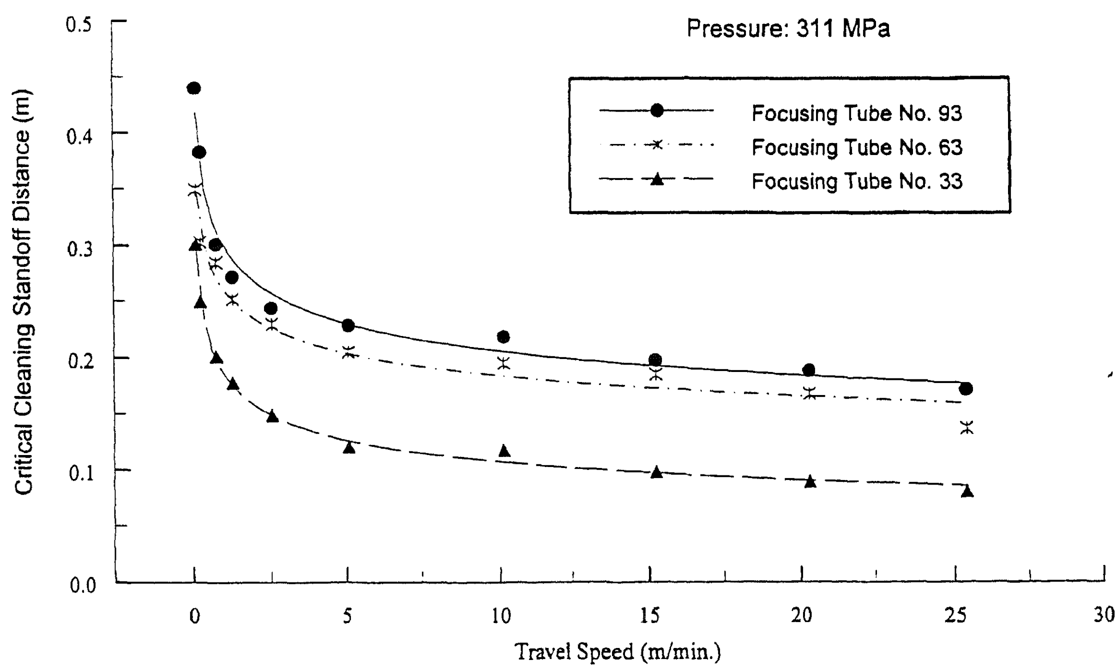

Fig. A.12 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 7 and three focusing tubes at 311 MPa.

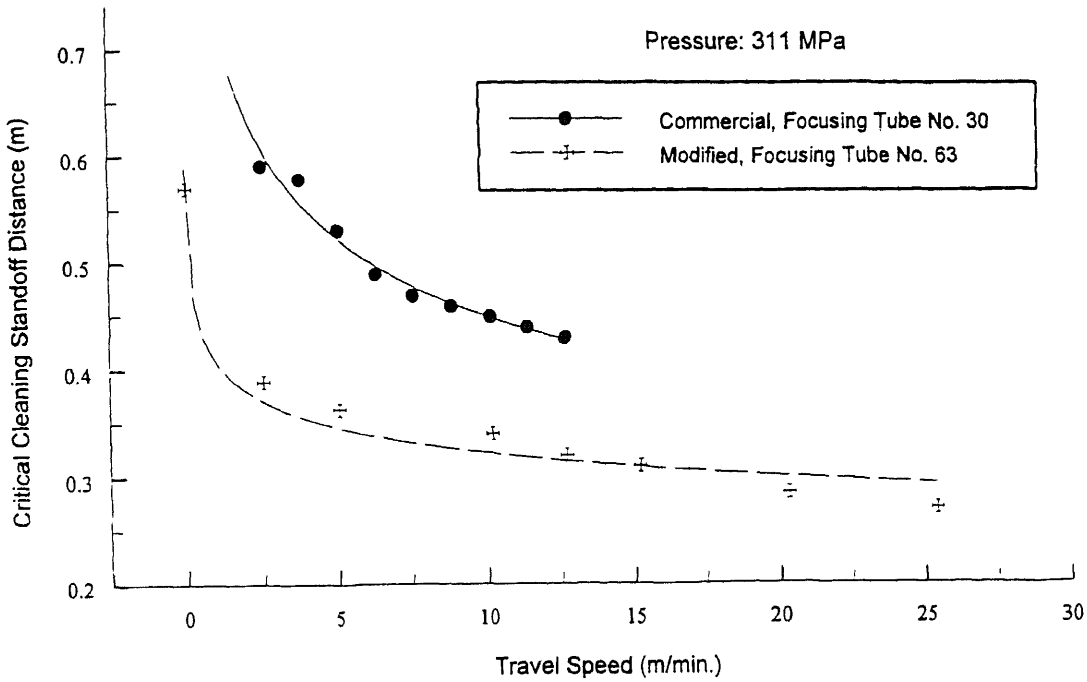

Fig. A.13 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with the commercial and modified nozzle body, nozzle no. 10 and focusing tubes at 311 MPa.

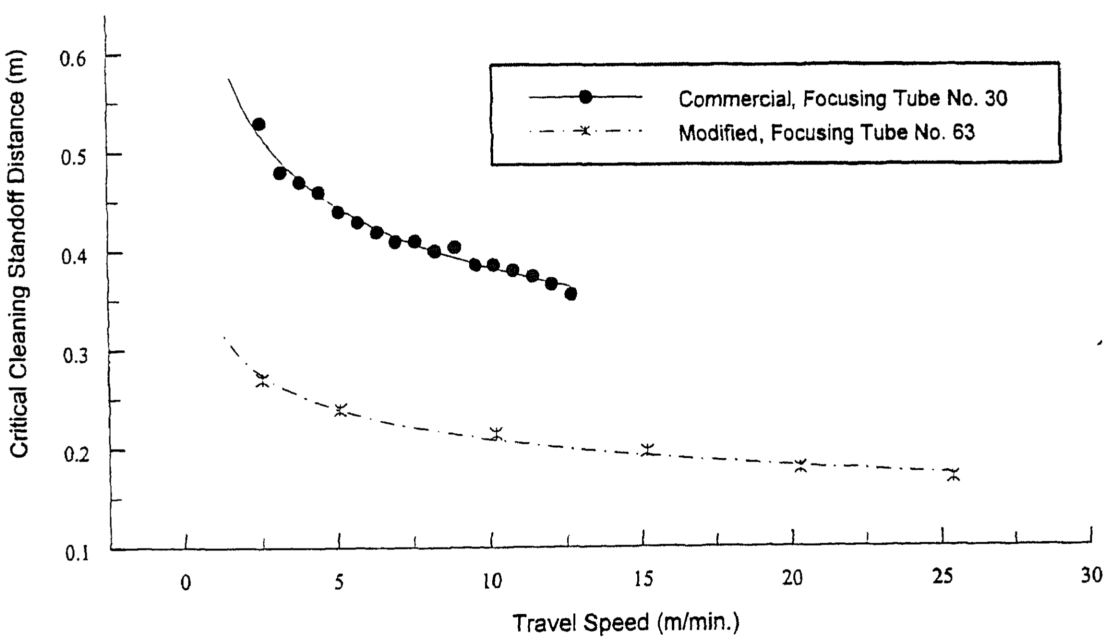

Fig. A.14 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with the commercial and modified nozzle body, nozzle no. 10 and focusing tubes at 311 MPa.

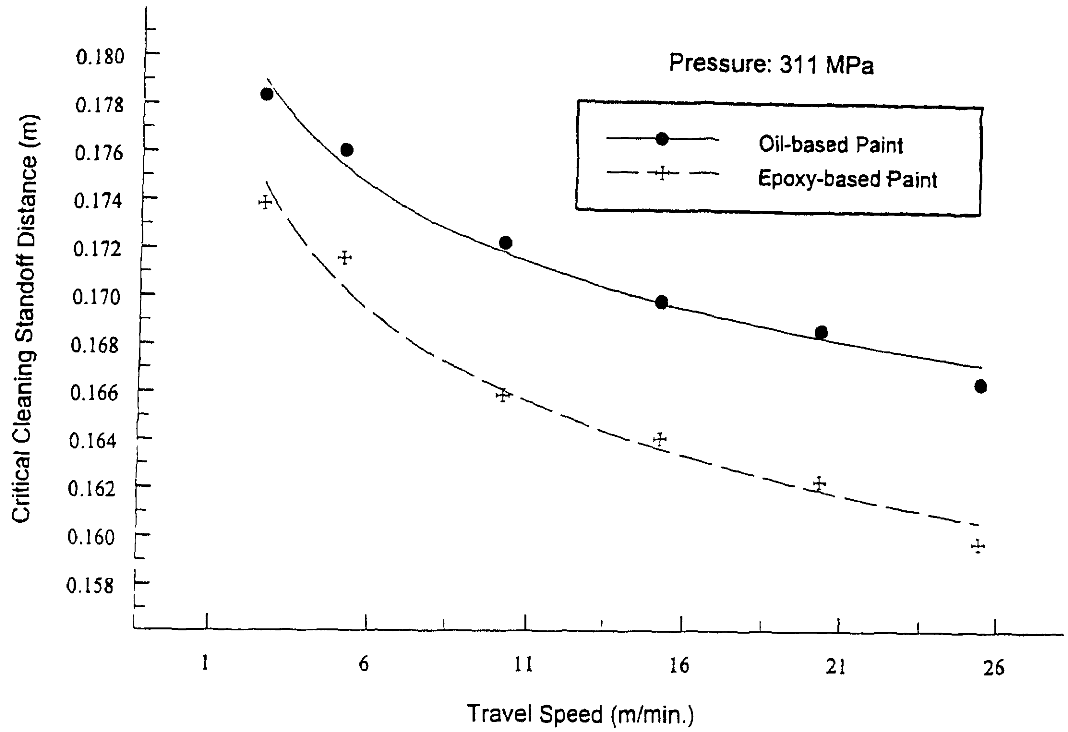

Fig. A.15 Critical cleaning standoff distance vs. travel speed for oil and epoxy based paint removal with the spiral nozzle body, nozzle no. 12 at 311 MPa.

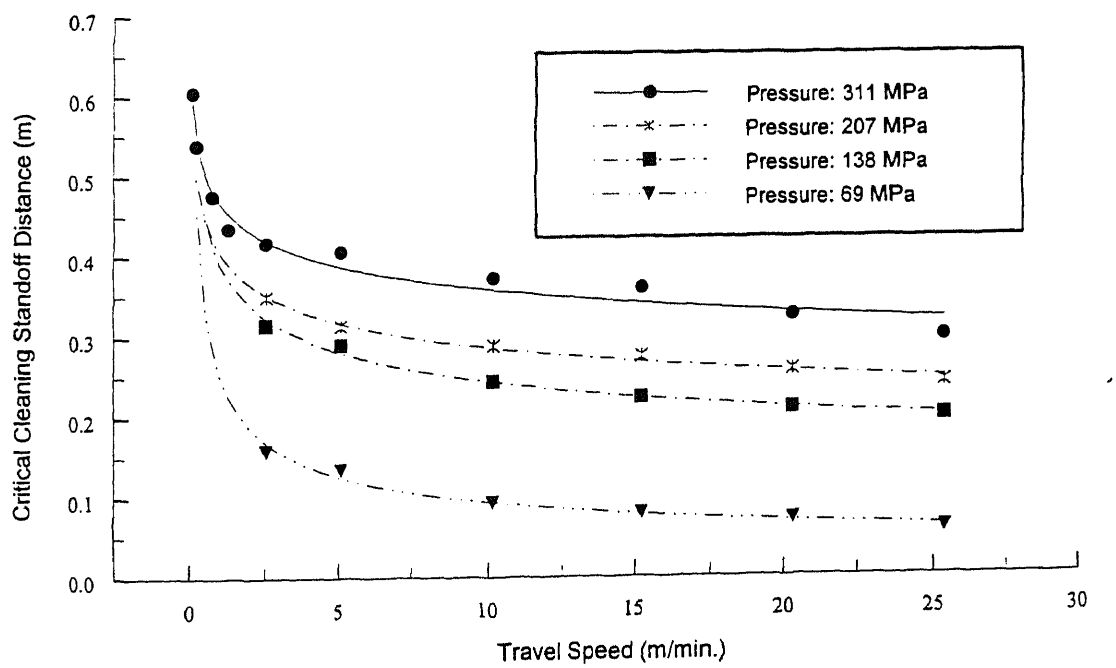

Fig. A.16 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 12 and focusing tube no. 63 at different water pressures.

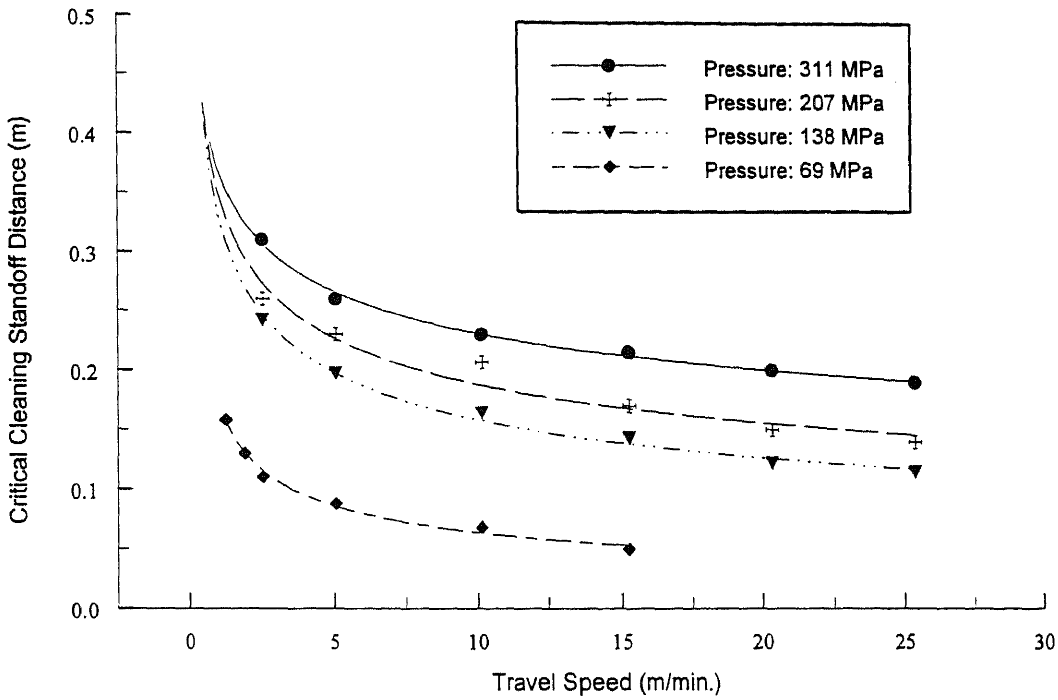

Fig. A.17 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with the modified nozzle body, nozzle no. 12 and focusing tube no. 63 at different water pressures.

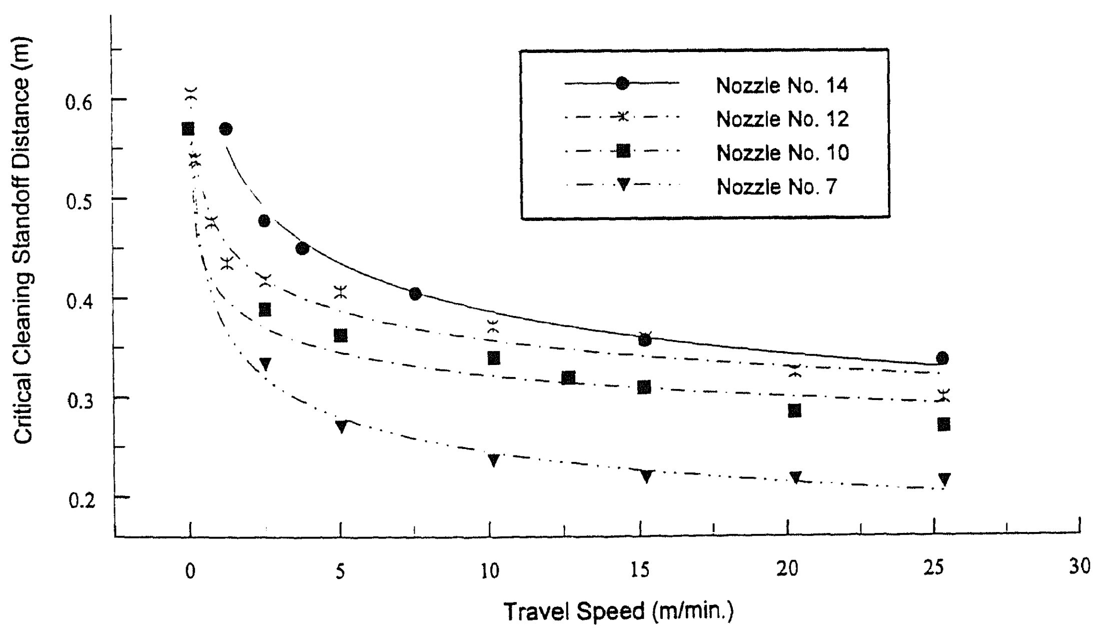

Fig. A.18 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with the modified nozzle body, different nozzles and focusing tube no. 63 at 311 MPa.

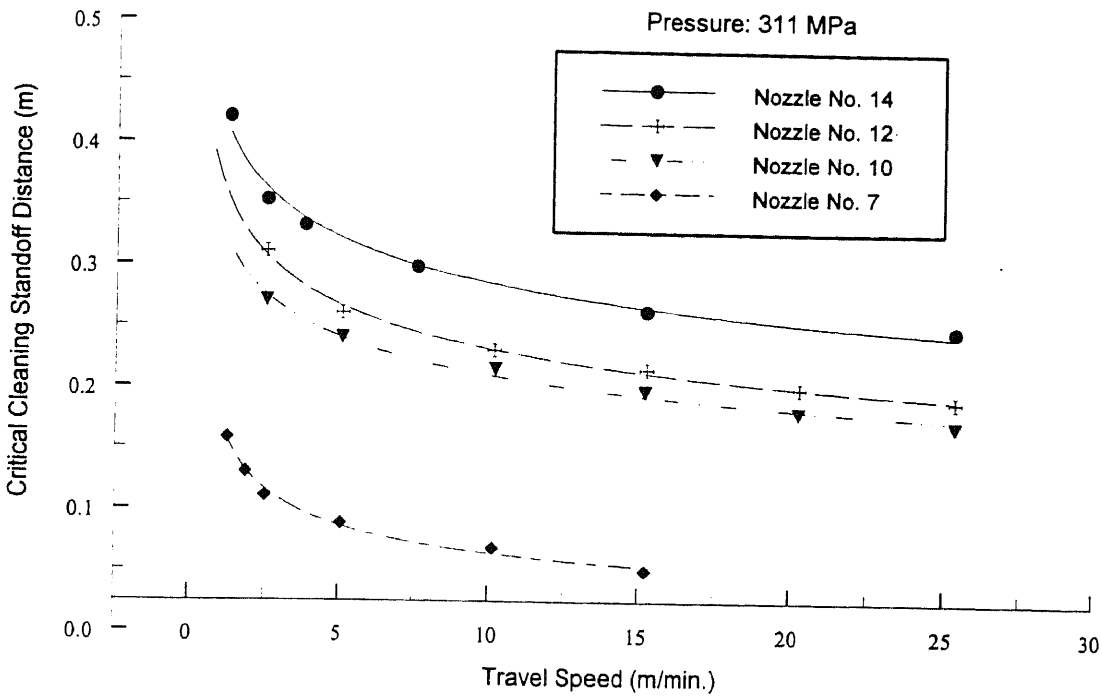

Fig. A.19 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with the modified nozzle body, different nozzles and focusing tube no. 63 at 311 MPa.

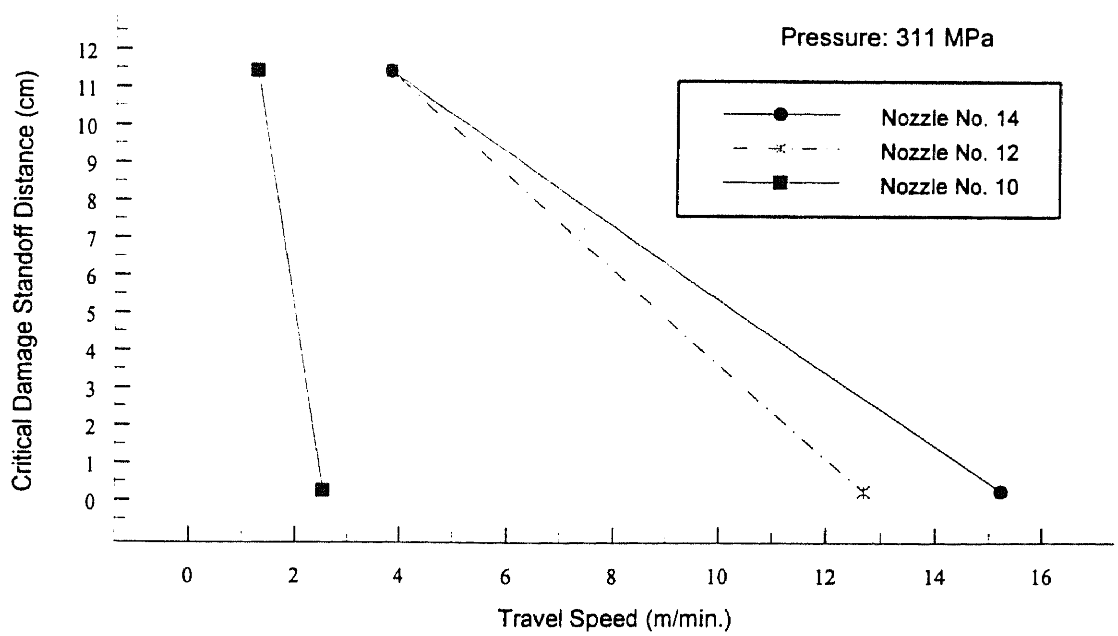

Fig. A.20 Critical damage standoff distance vs. travel speed for Glass Lined #3008 surface erosion with the modified nozzle body, different nozzles and focusing tube no. 93 at 311 MPa.

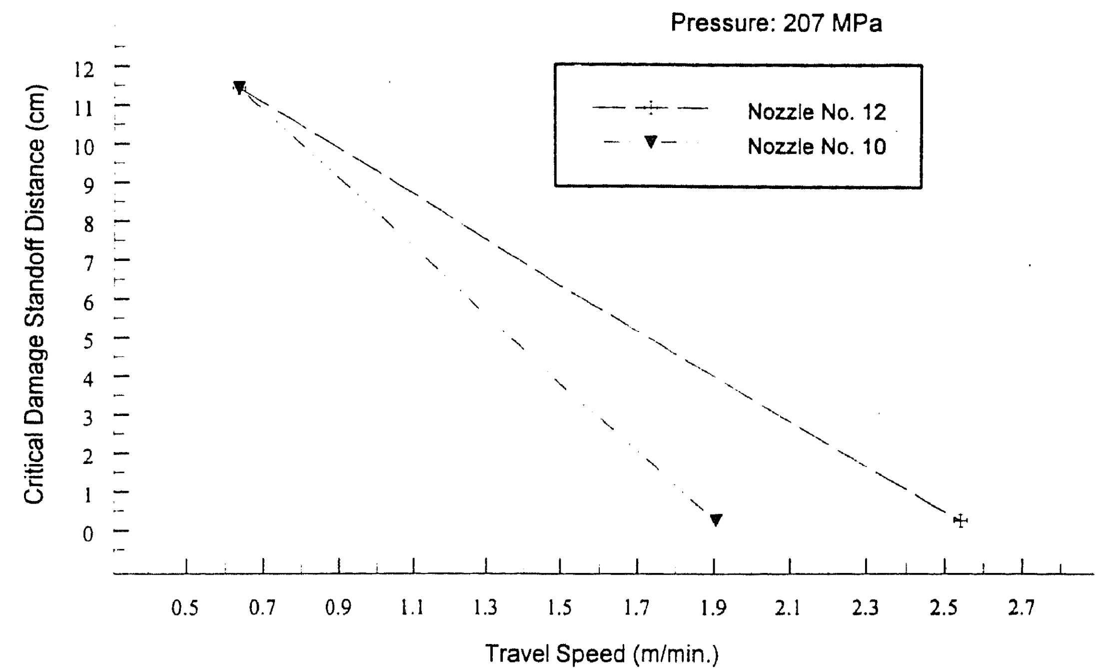

Fig. A.21 Critical damage standoff distance vs. travel speed for Glass Lined #3008 surface erosion with the modified nozzle body, different nozzles and focusing tube no. 93 at 207 MPa.

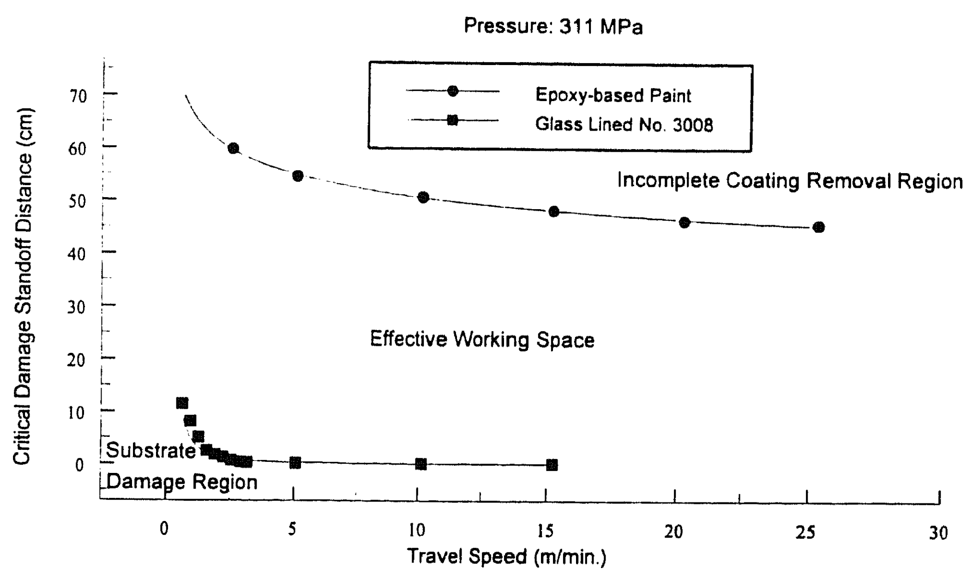

Fig. A.22 Critical damage and cleaning standoff distance vs. travel speed for Glass Lined #3008 surface erosion and epoxy-based paint with the modified nozzle body, nozzle no. 14 and focusing tube no. 93 at 311 MPa.

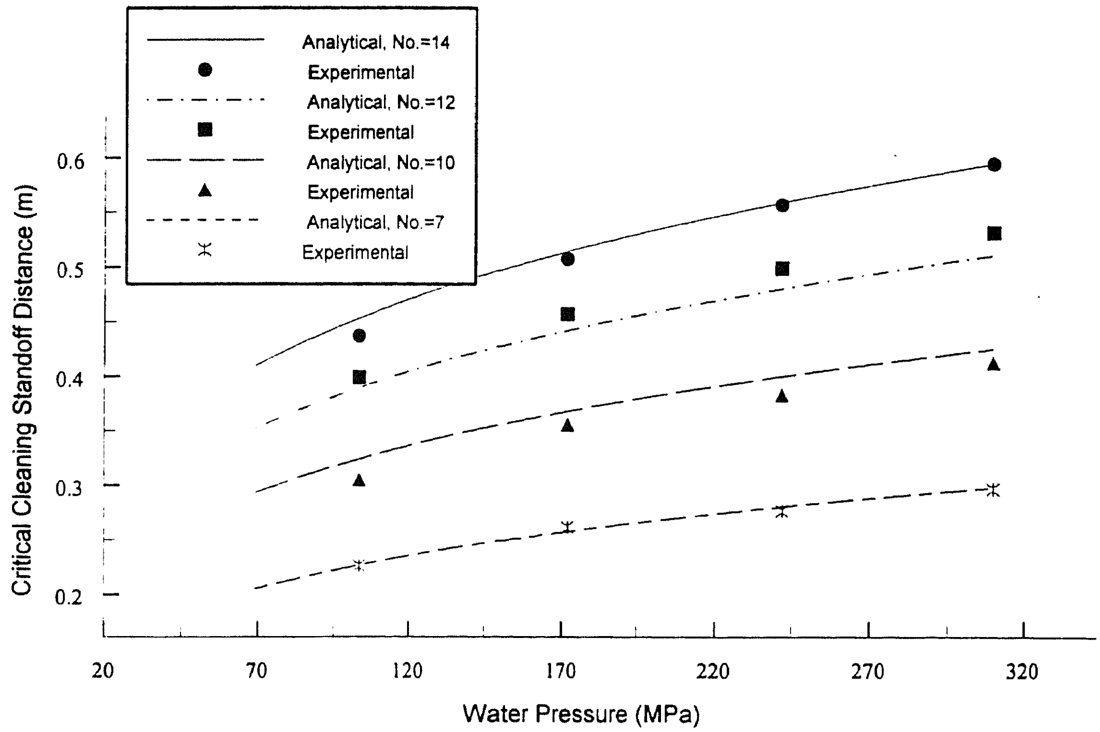

Fig. A.23 Critical cleaning standoff distance vs. water pressure for stationary jet oil-based paint removal with four different sapphire nozzles.

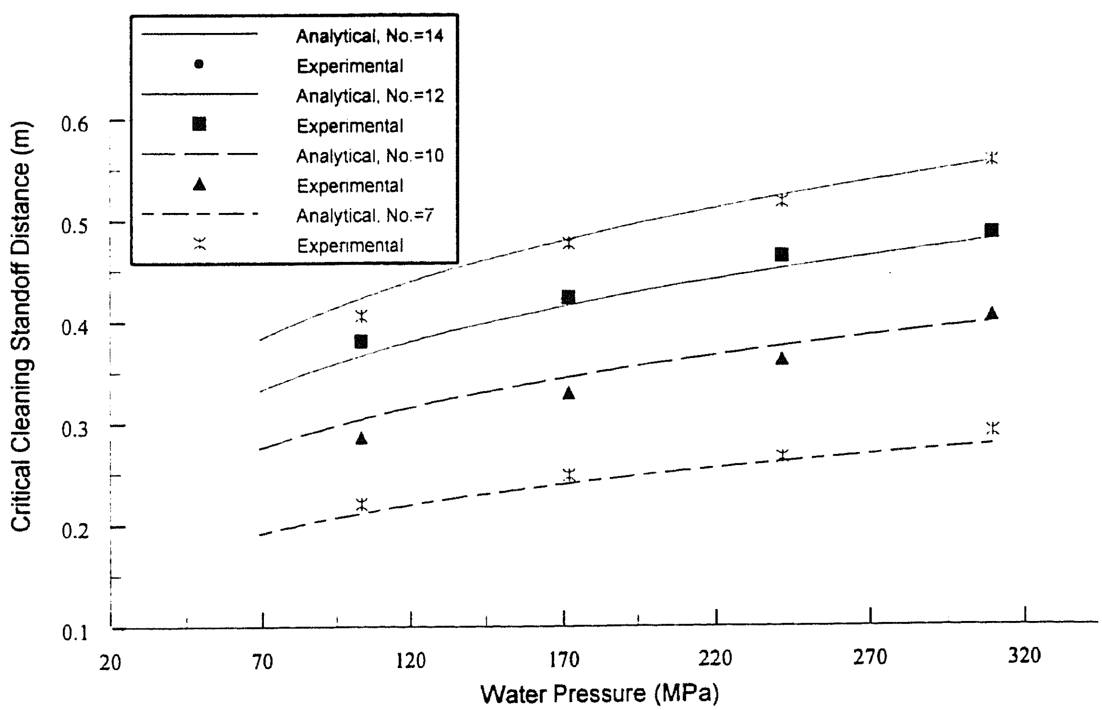

Fig. A.24 Critical cleaning standoff distance vs. water pressure for stationary jet epoxy-based paint removal with four different sapphire nozzles.

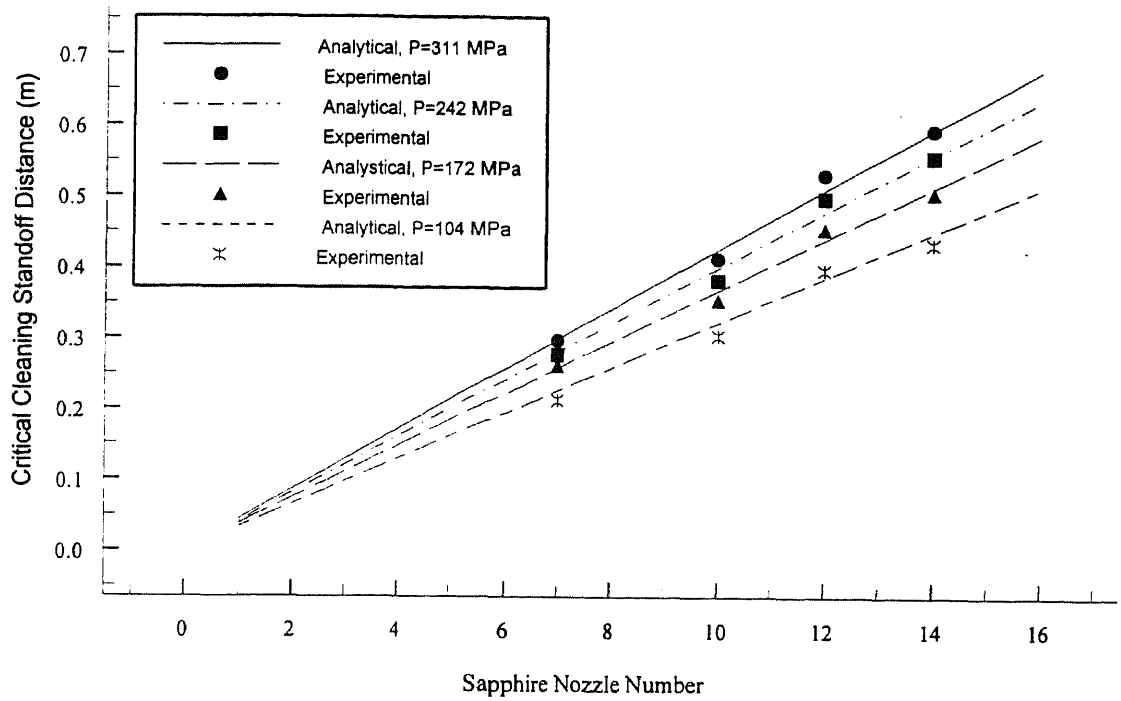

Fig. A.25 Critical cleaning standoff distance vs. sapphire nozzle number for stationary jet oil-based paint removal under four different water pressures.

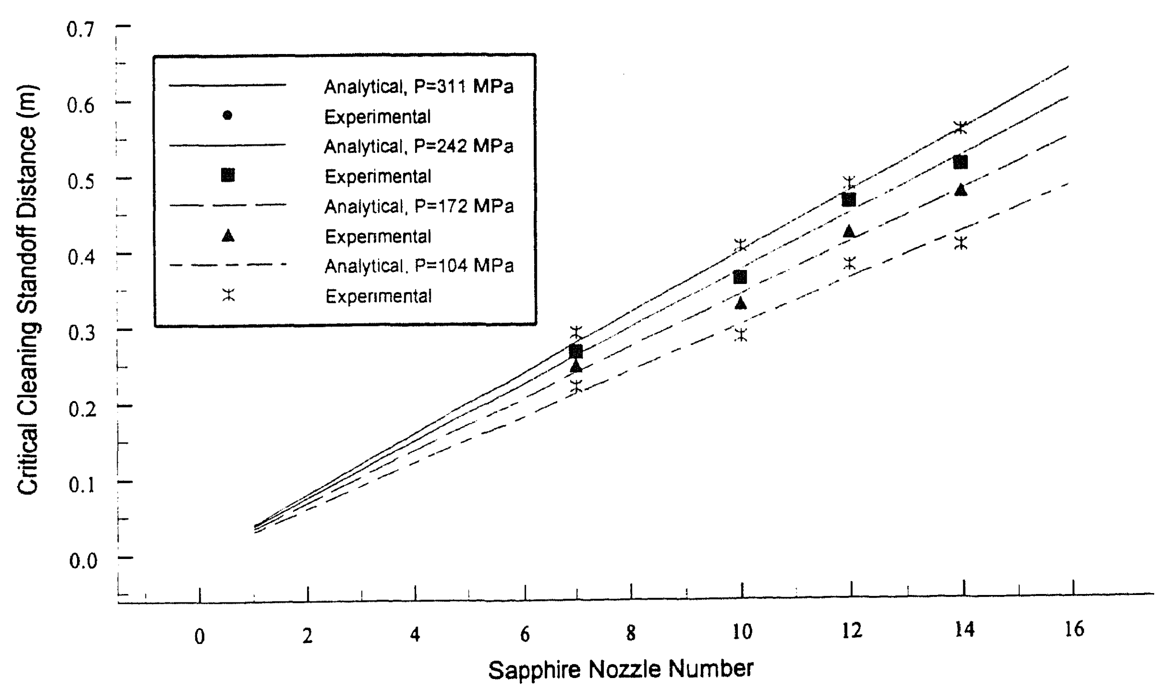

Fig. A.26 Critical cleaning standoff distance vs. sapphire nozzle number for stationary jet epoxy-based paint removal under four different water pressures.

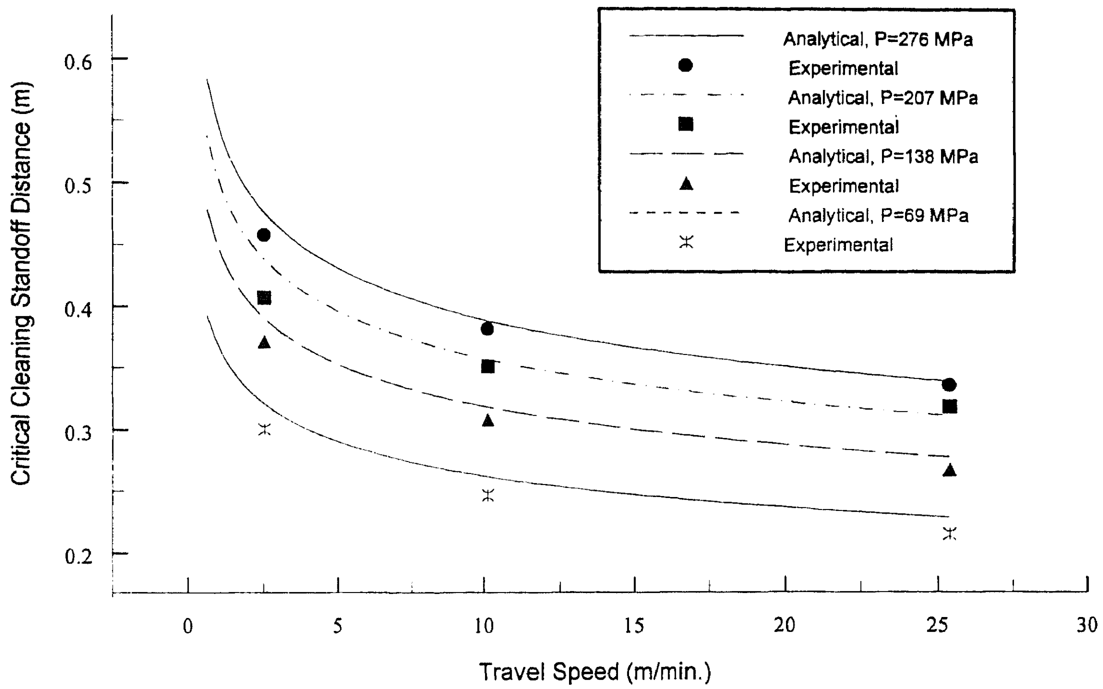

Fig. A.27 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with sapphire nozzle no. 14 under four different water pressures.

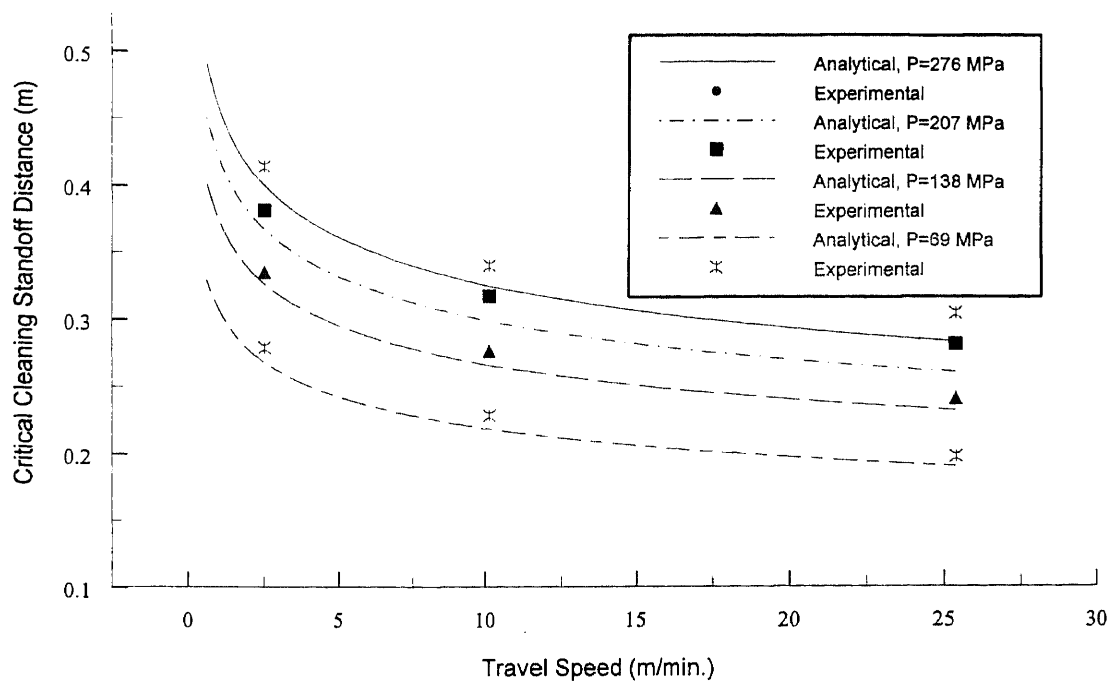

Fig. A.28 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with sapphire nozzle no. 12 under four different water pressures.

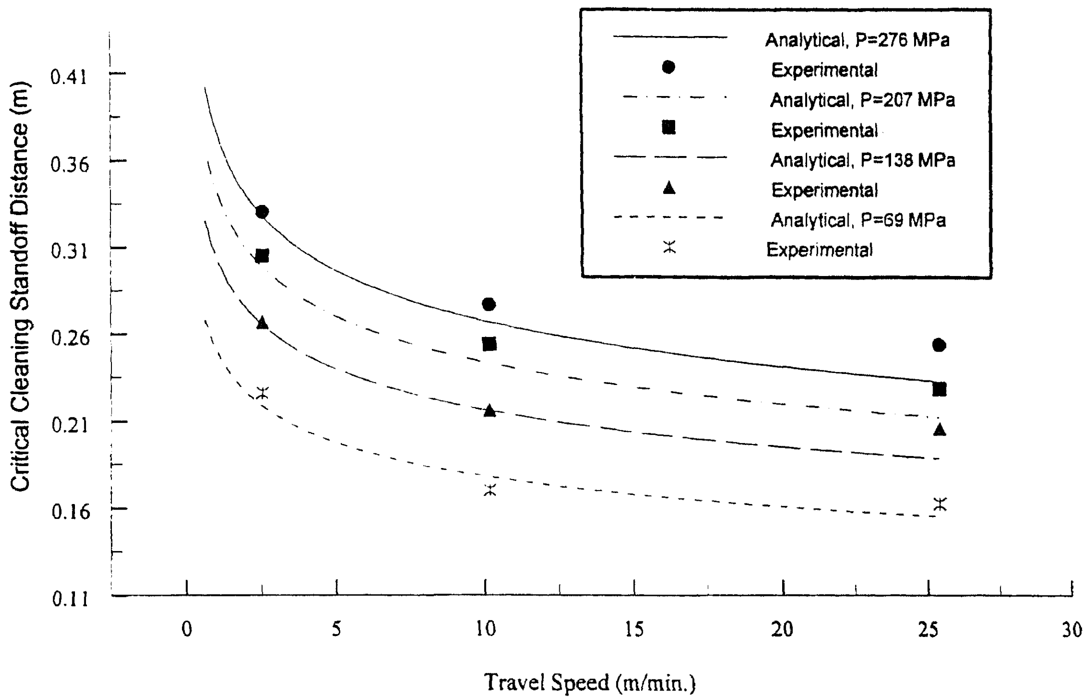

Fig. A.29 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with sapphire nozzle no. 10 under four different water pressures.

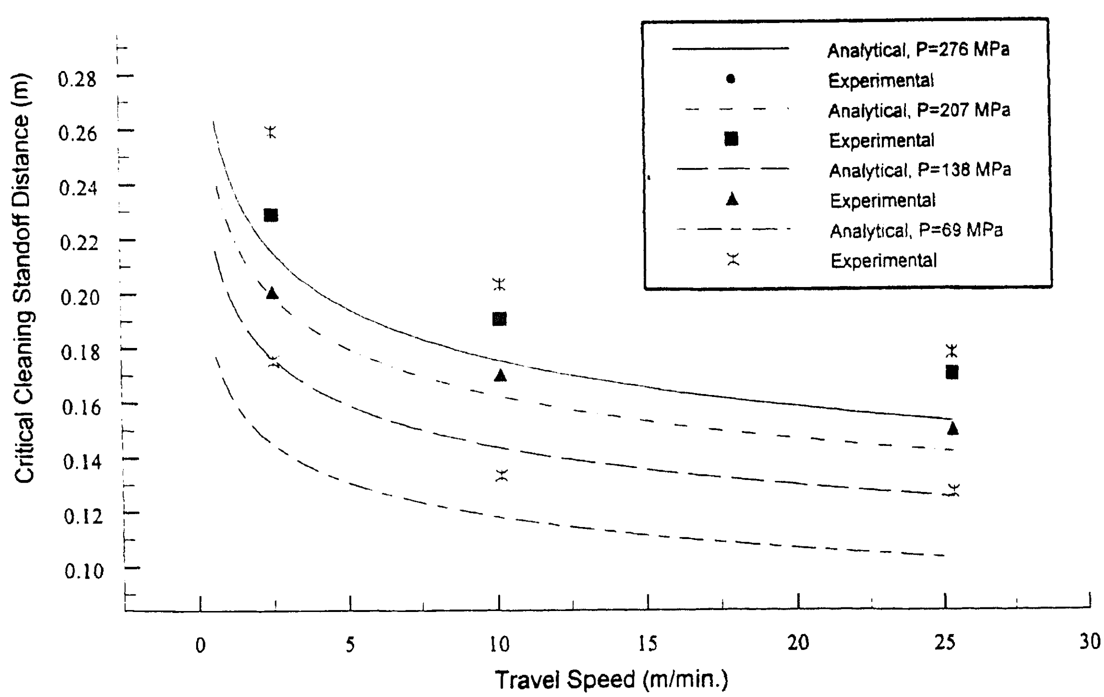

Fig. A.30 Critical cleaning standoff distance vs. travel speed for oil-based paint removal with sapphire nozzle no. 7 under four different water pressures.

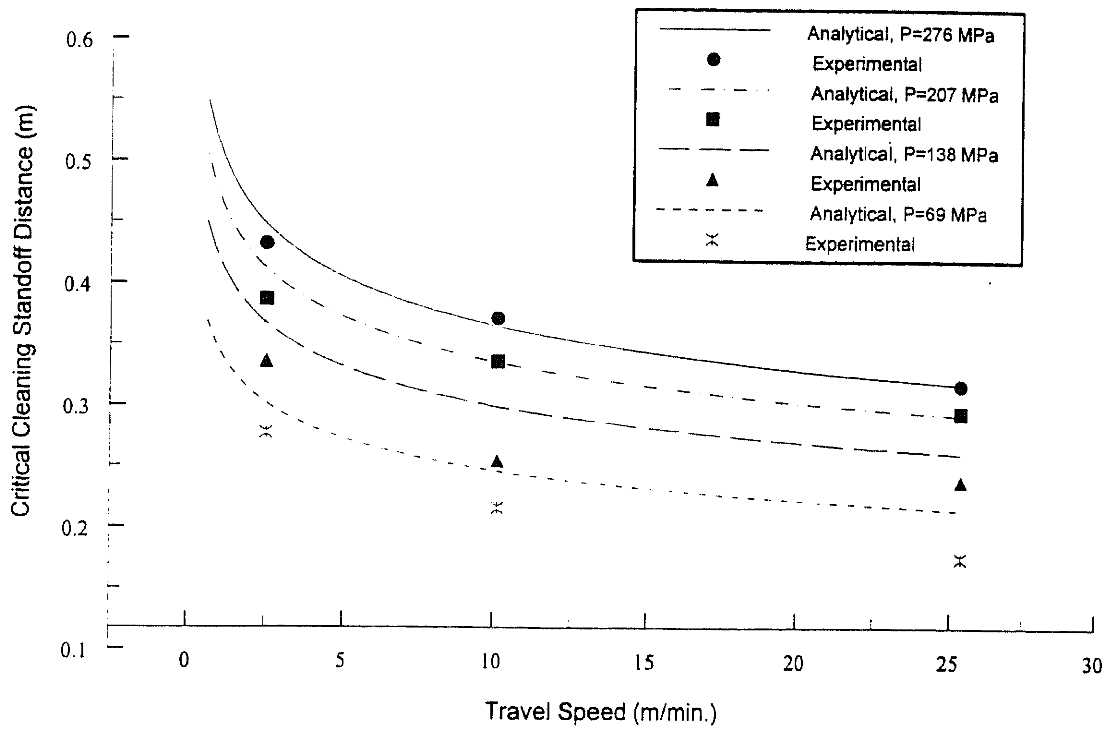

Fig. A.31 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 14 under four different water pressures.

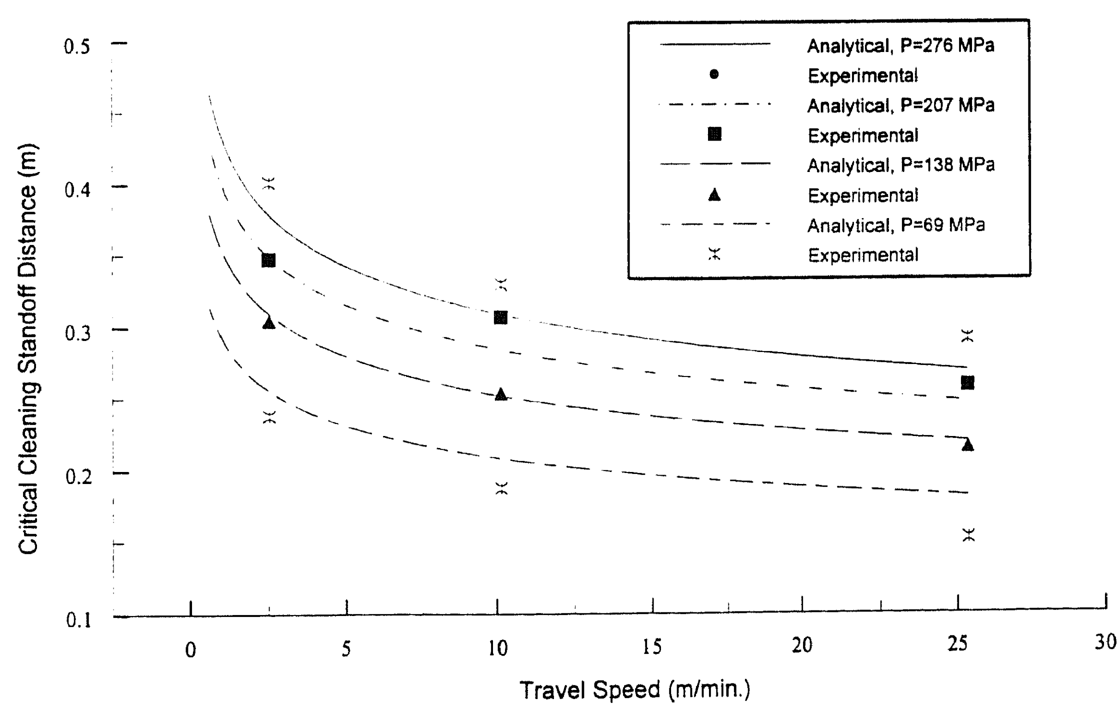

Fig. A.32 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 12 under four different water pressures.

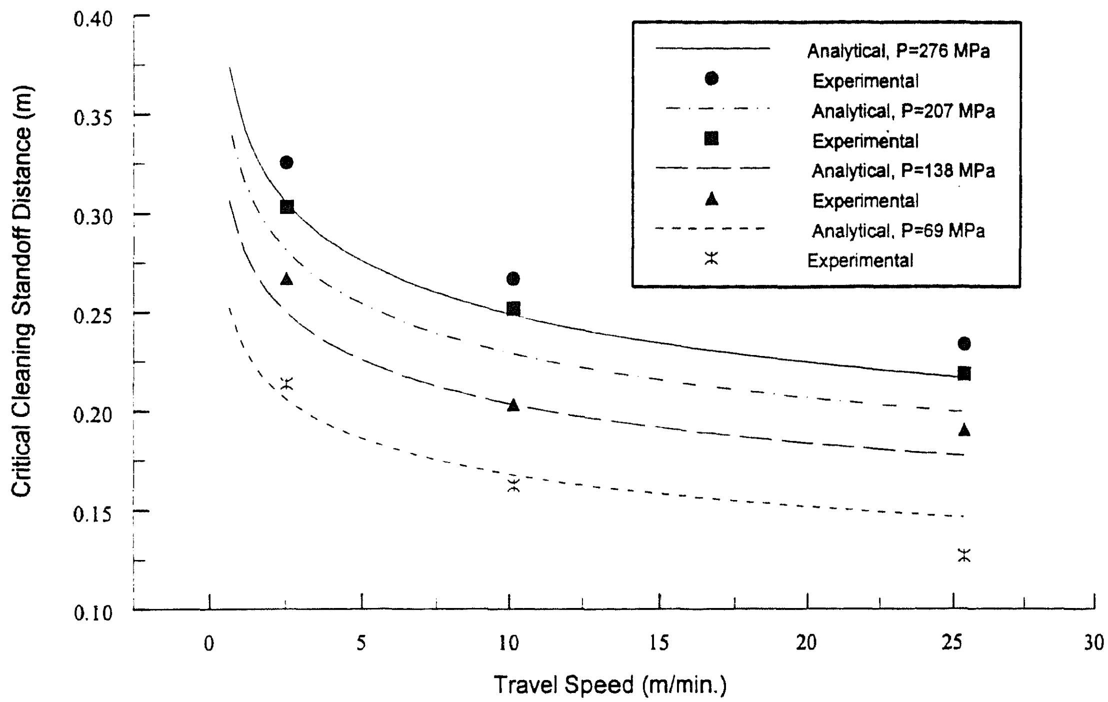

Fig. A.33 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 10 under four different water pressures.

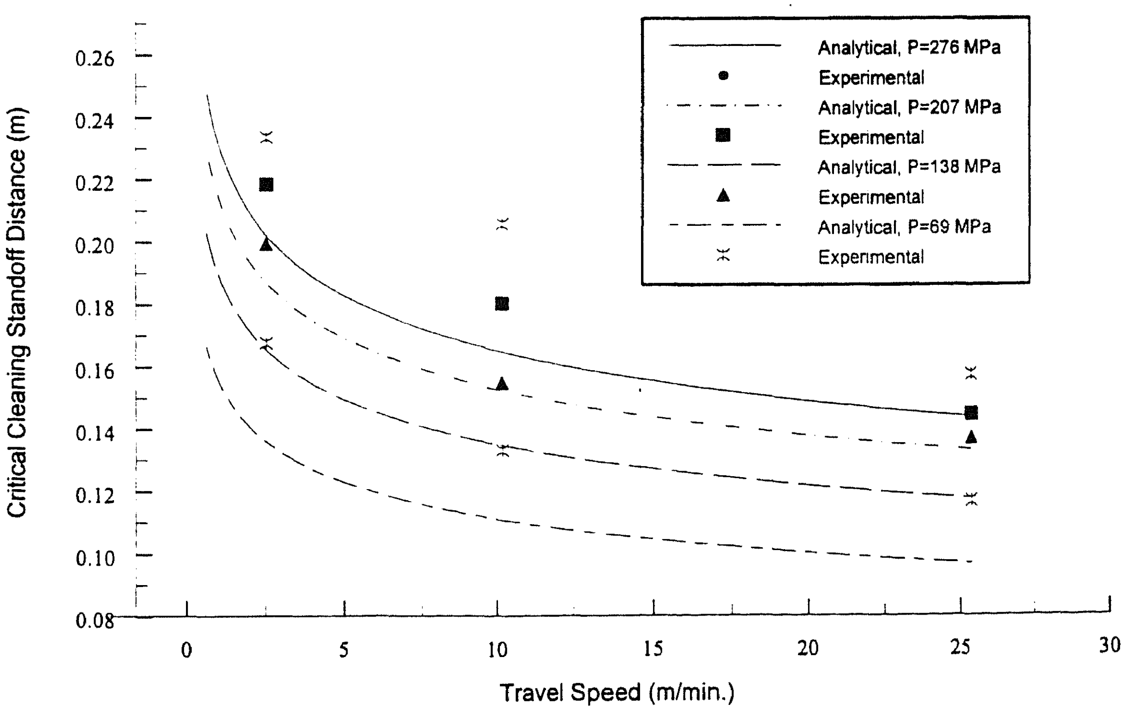

Fig. A.34 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 7 under four different water pressures.

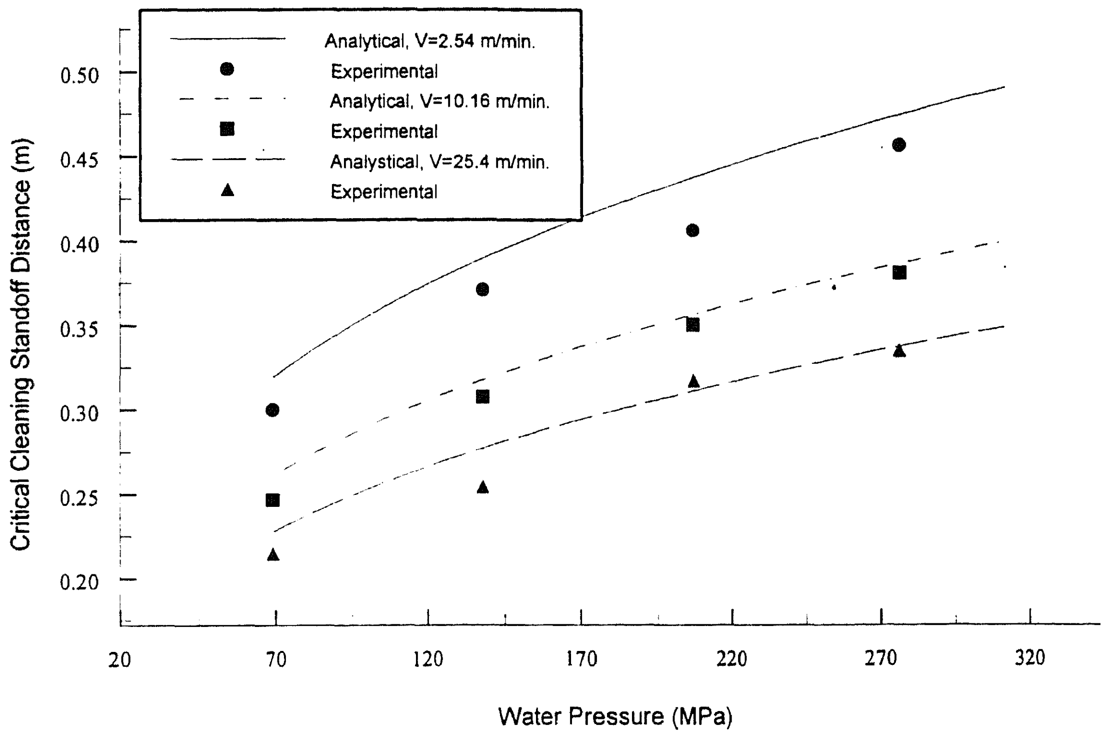

Fig. A.35 Critical cleaning standoff distance vs. water pressure for oil-based paint removal with sapphire nozzle no. 14 at three different travel speeds.

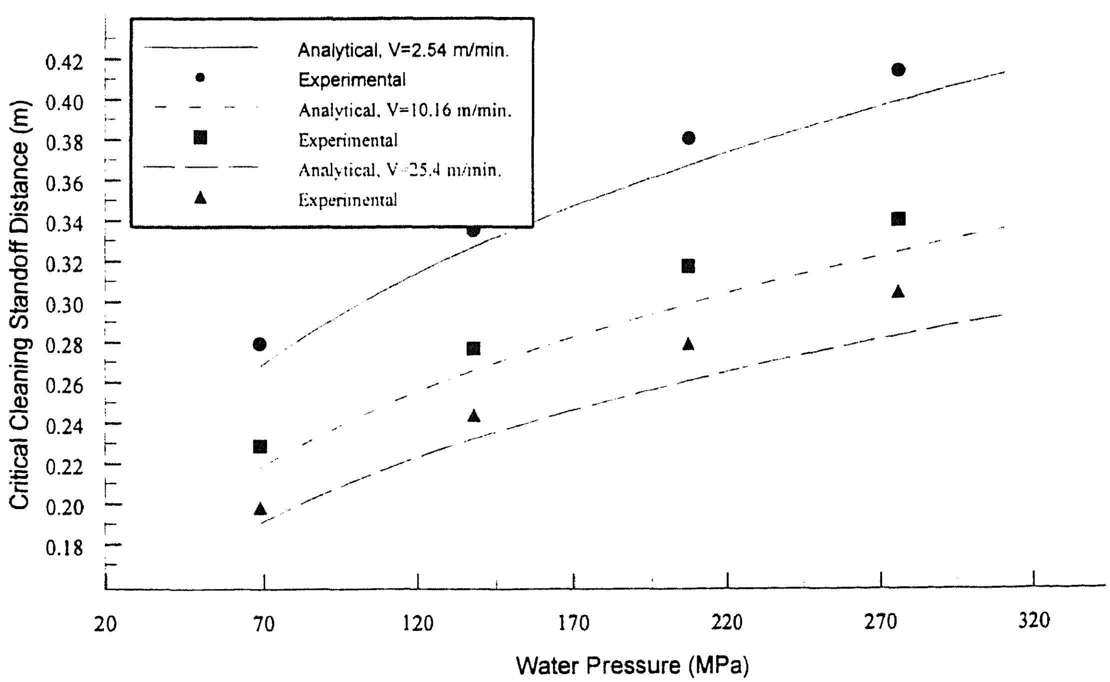

Fig. A.36 Critical cleaning standoff distance vs. water pressure for oil-based paint removal with sapphire nozzle no. 12 at three different travel speeds.

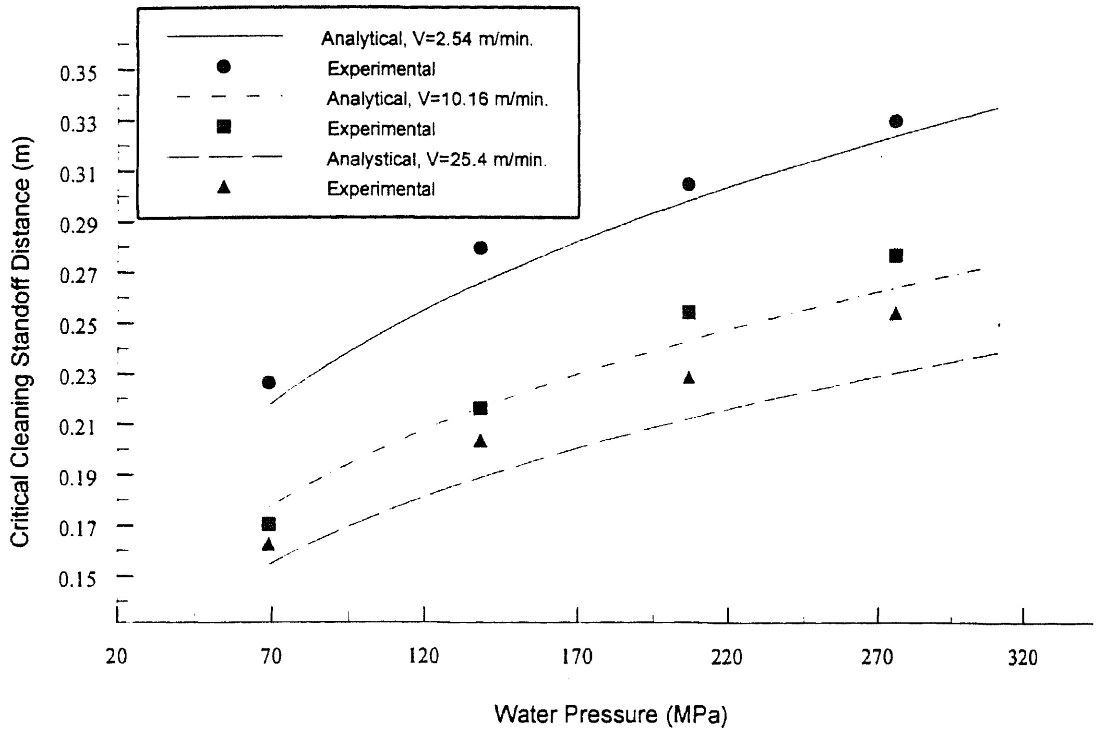

Fig. A.37 Critical cleaning standoff distance vs. water pressure for oil-based paint removal with sapphire nozzle no. 10 at three different travel speeds.

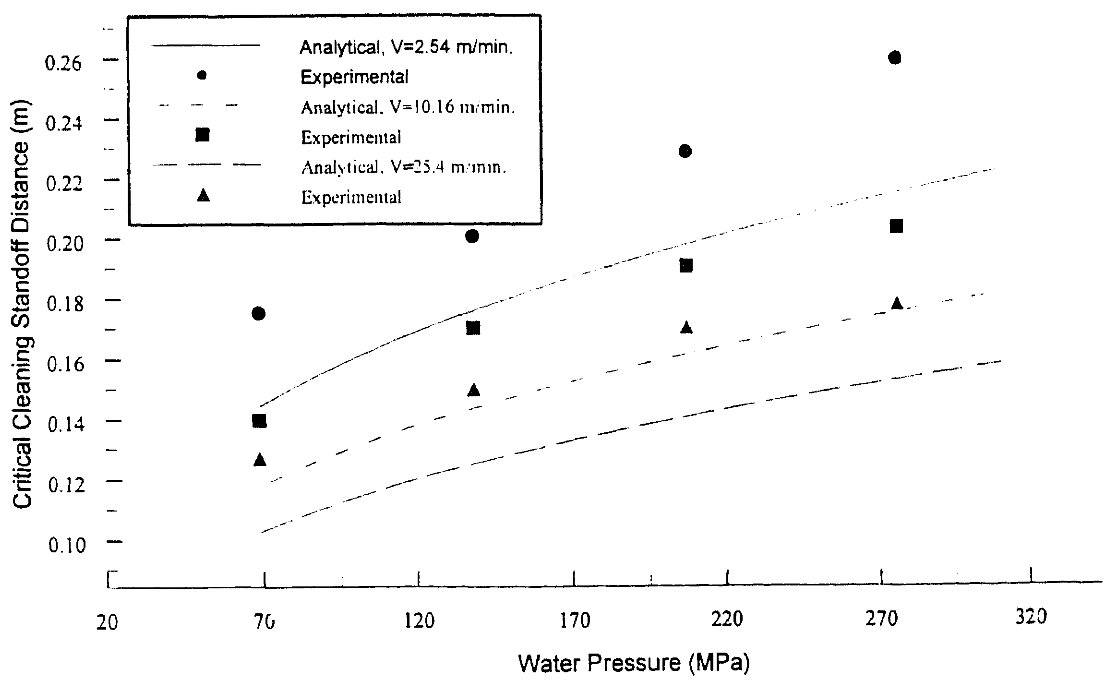

Fig. A.38 Critical cleaning standoff distance vs. water pressure for oil-based paint removal with sapphire nozzle no. 7 at three different travel speeds.

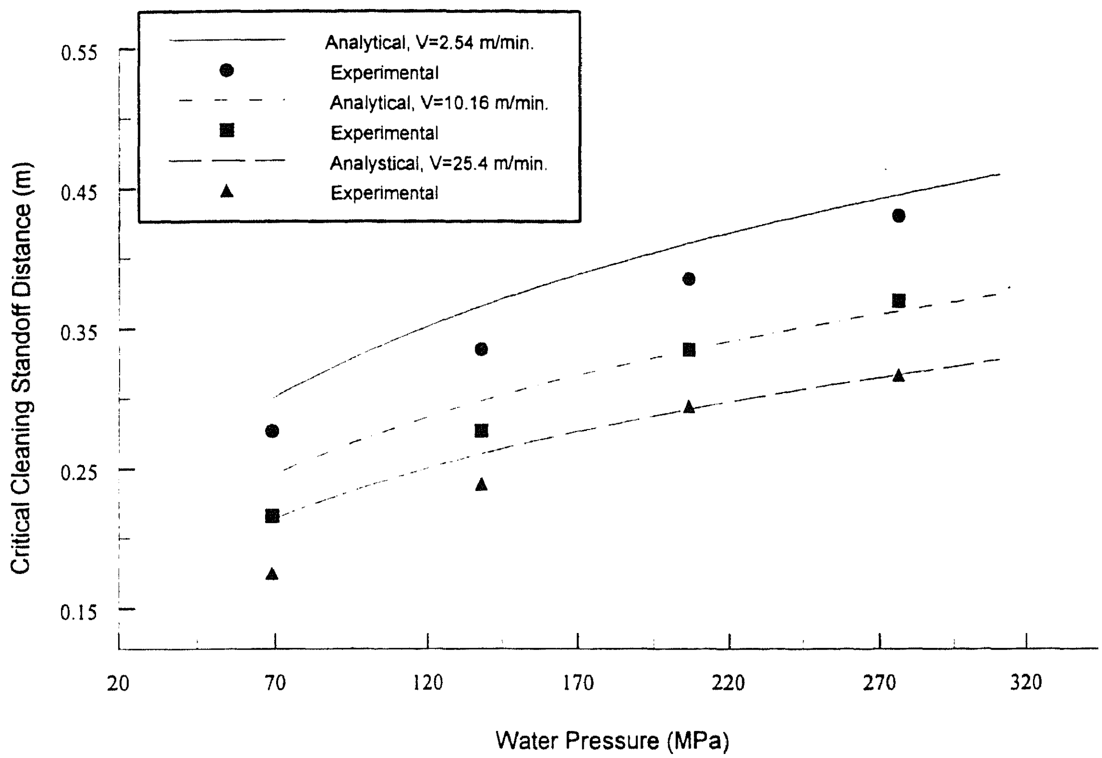

Fig. A.39 Critical cleaning standoff distance vs. water pressure for epoxy-based paint removal with sapphire nozzle no. 14 at three different travel speeds.

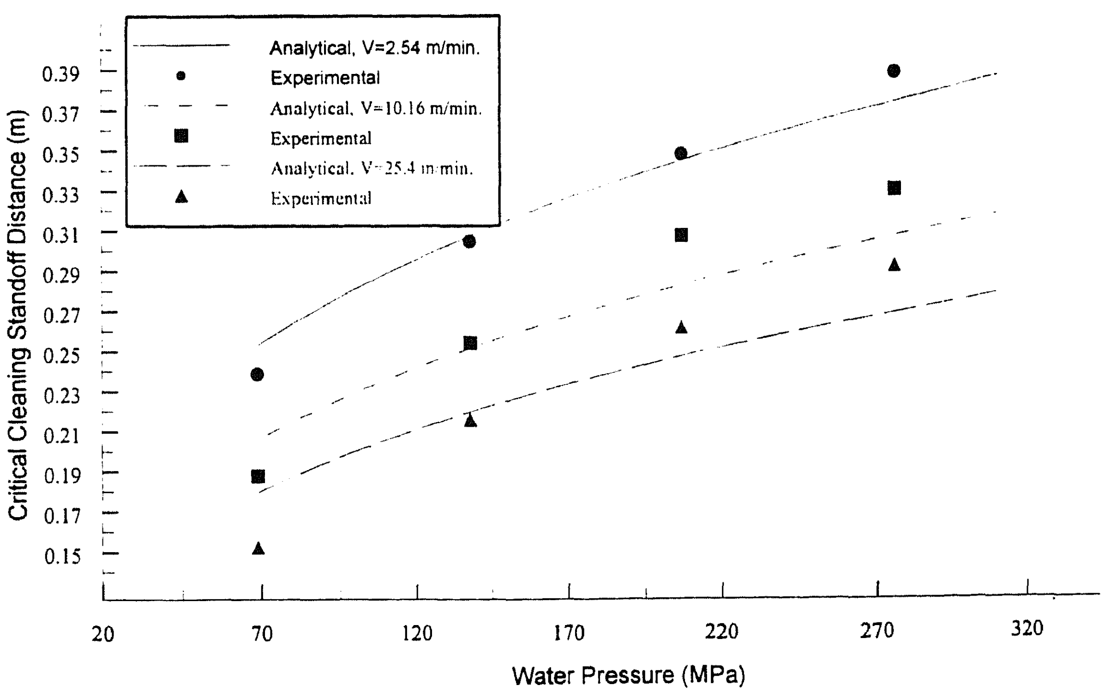

Fig. A.40 Critical cleaning standoff distance vs. water pressure for epoxy-based paint removal with sapphire nozzle no. 12 at three different travel speeds.

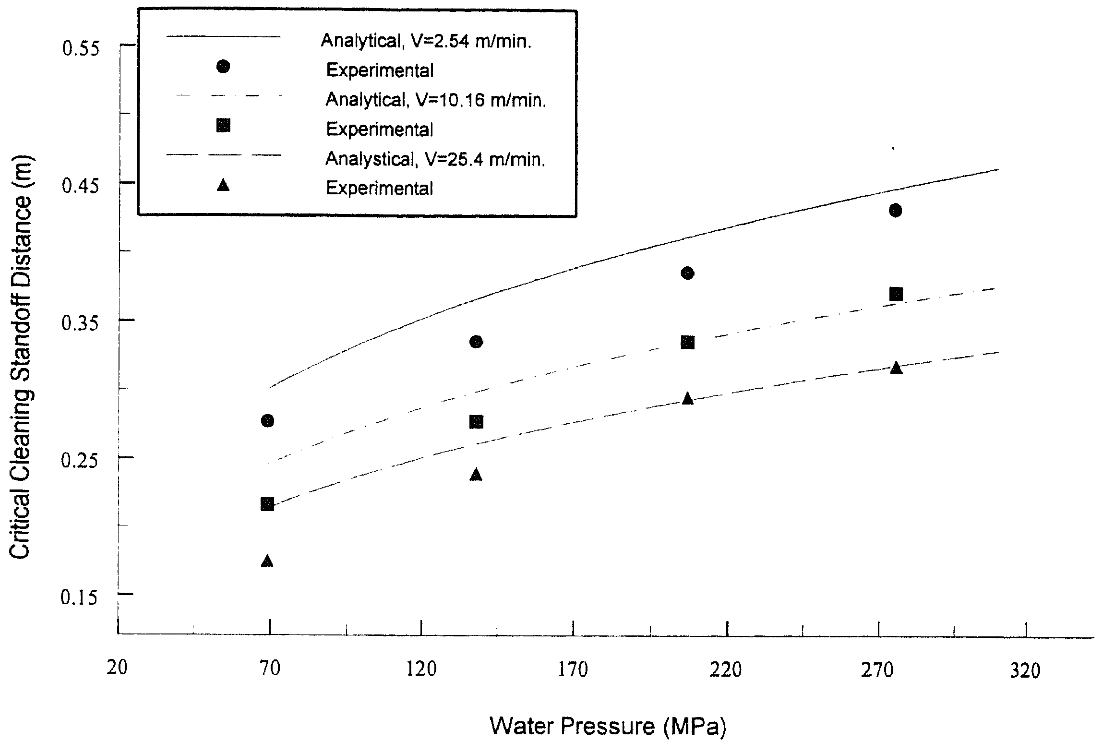

Fig. A.41 Critical cleaning standoff distance vs. water pressure for epoxy-based paint removal with sapphire nozzle no. 14 at three different travel speeds.

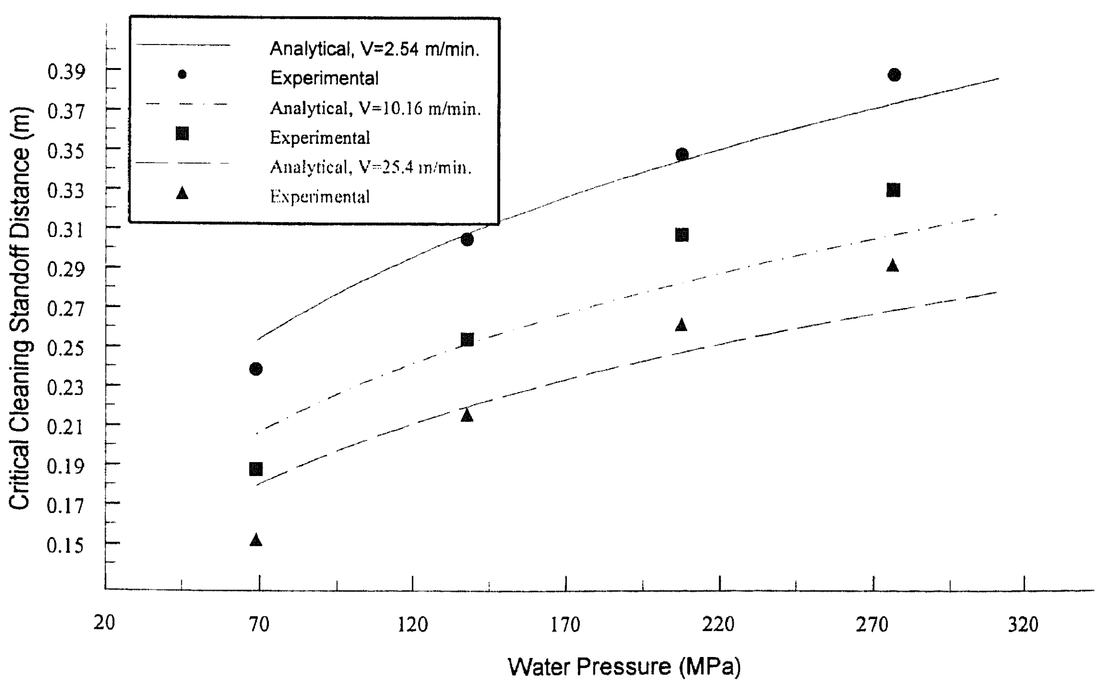

Fig. A.42 Critical cleaning standoff distance vs. water pressure for epoxy-based paint removal with sapphire nozzle no. 12 at three different travel speeds.

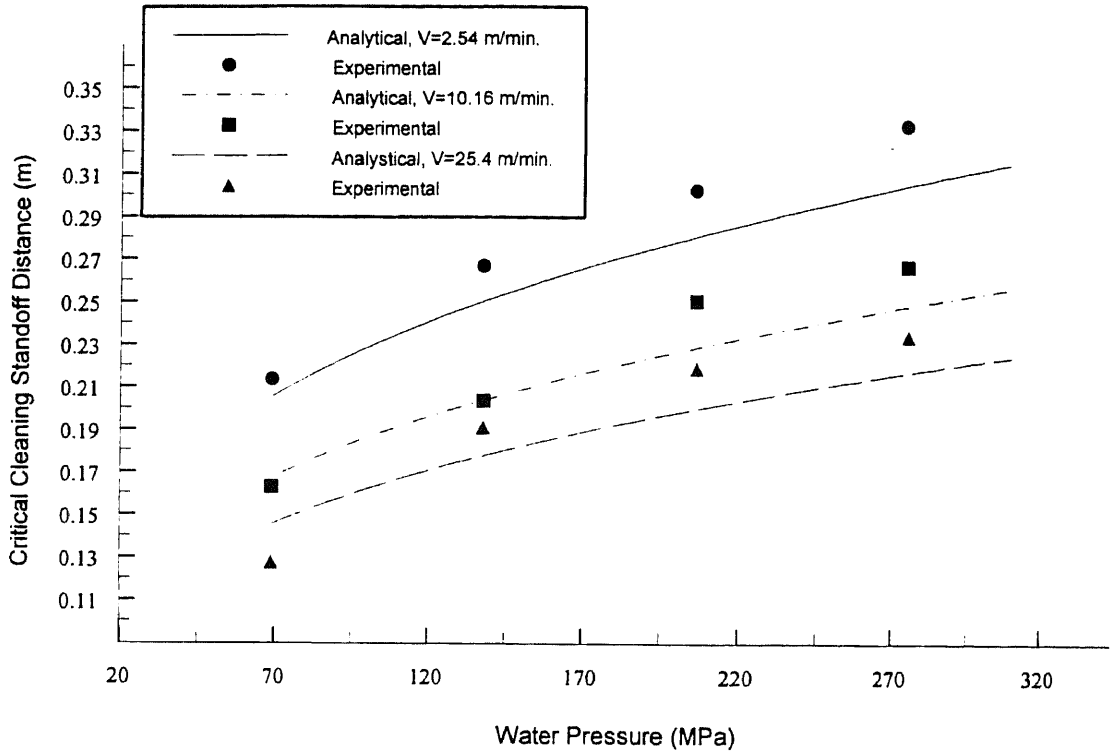

Fig. A.43 Critical cleaning standoff distance vs. water pressure for epoxy-based paint removal with sapphire nozzle no. 10 at three different travel speeds.

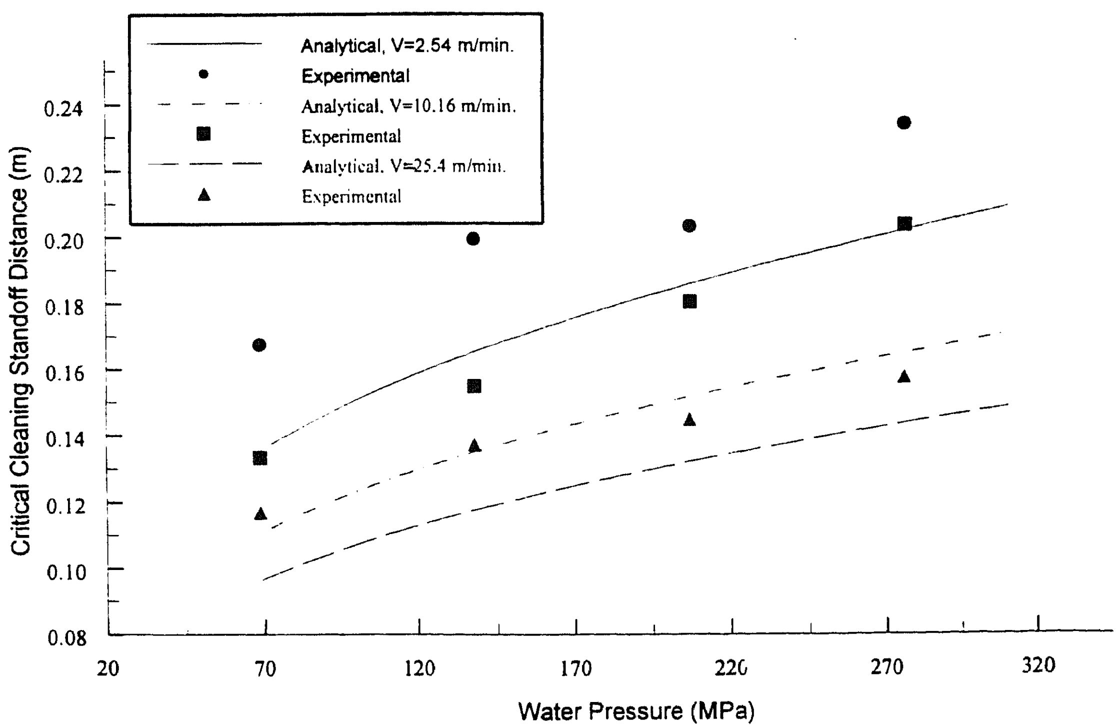

Fig. A.44 Critical cleaning standoff distance vs. water pressure for epoxy-based paint removal with sapphire nozzle no. 7 at three different travel speeds.

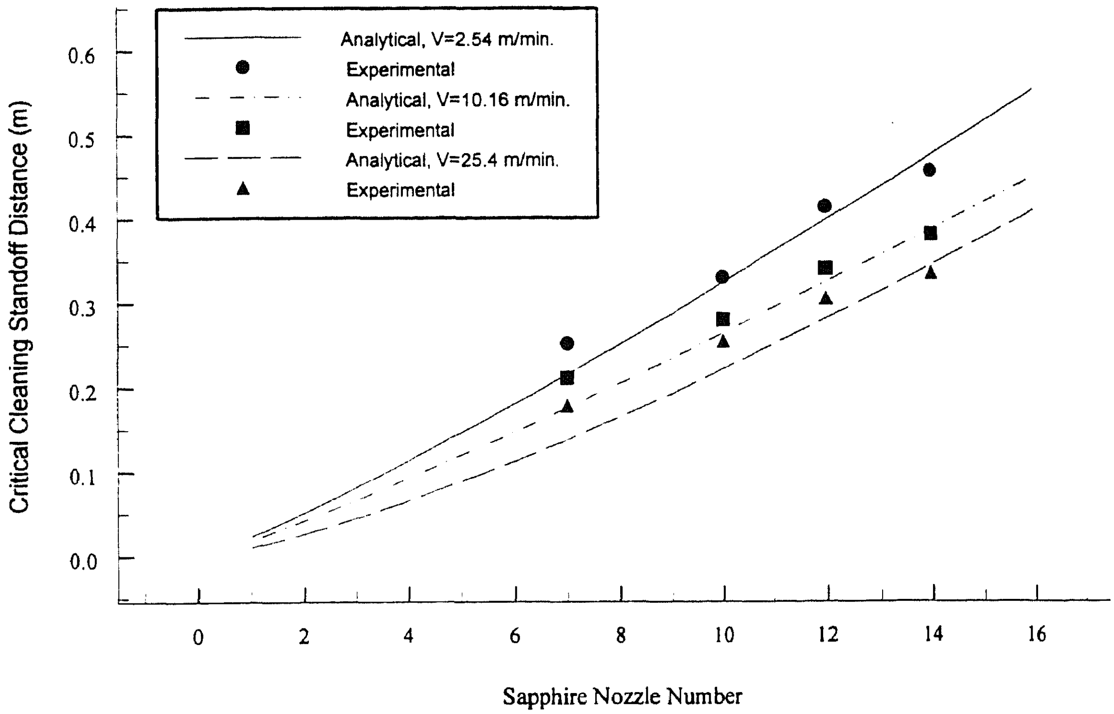

Fig. A.45 Critical cleaning standoff distance vs. nozzle number for oil-based paint removal at 276 MPa water pressure at three different travel speeds.

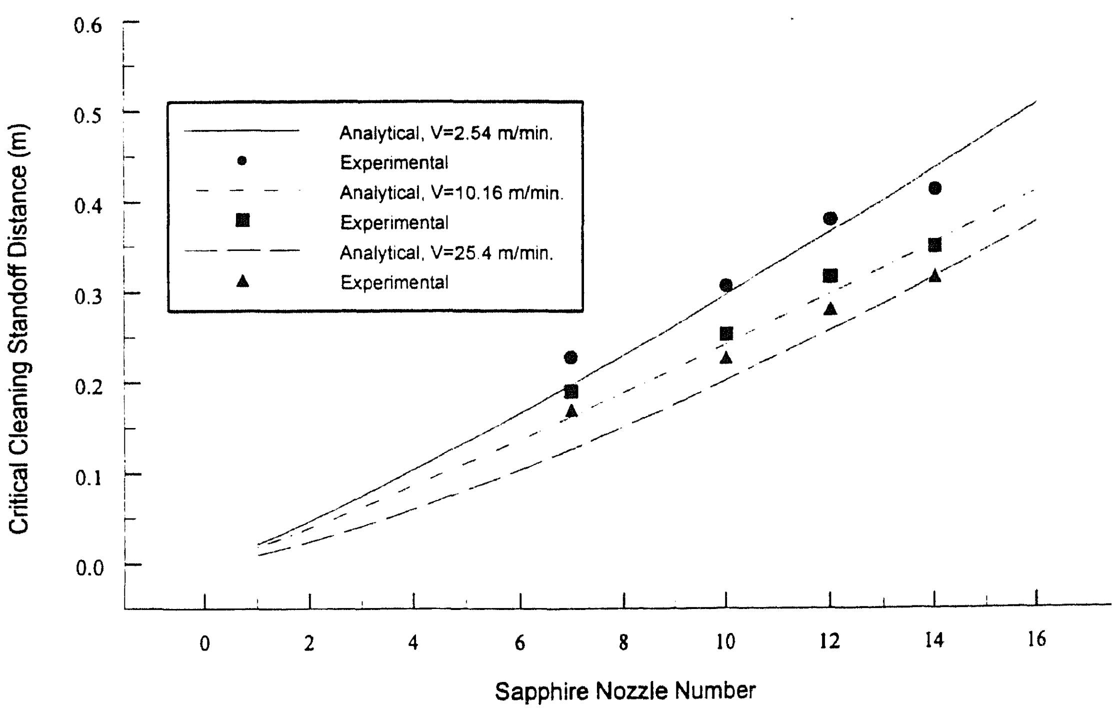

Fig. A.46 Critical cleaning standoff distance vs. nozzle number for oil-based paint removal at 207 MPa water pressure at three different travel speeds.

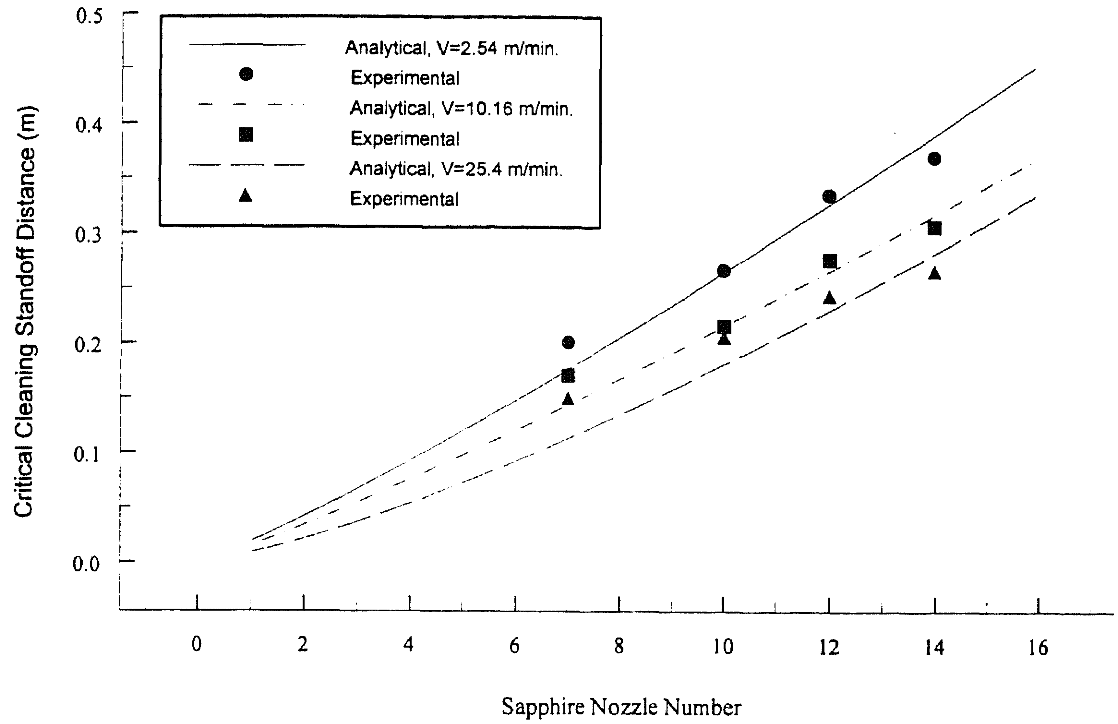

Fig. A.47 Critical cleaning standoff distance vs. nozzle number for oil-based paint removal at 138 MPa water pressure at three different travel speeds.

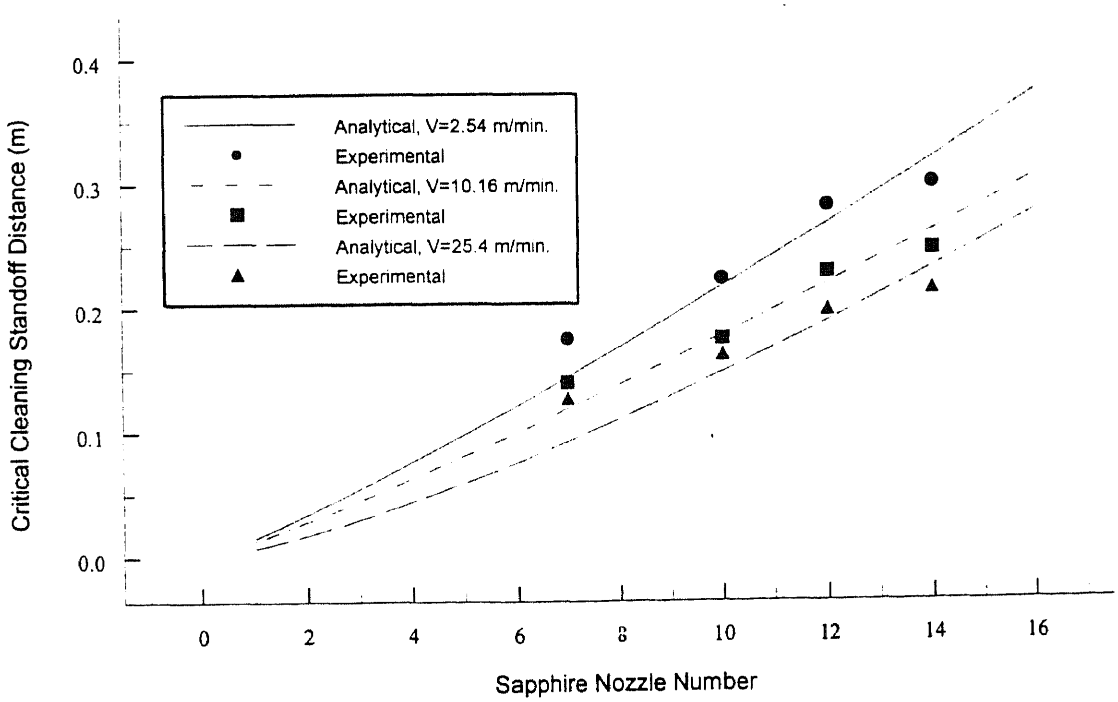

Fig. A.48 Critical cleaning standoff distance vs. nozzle number for oil-based paint removal at 69 MPa water pressure at three different travel speeds.

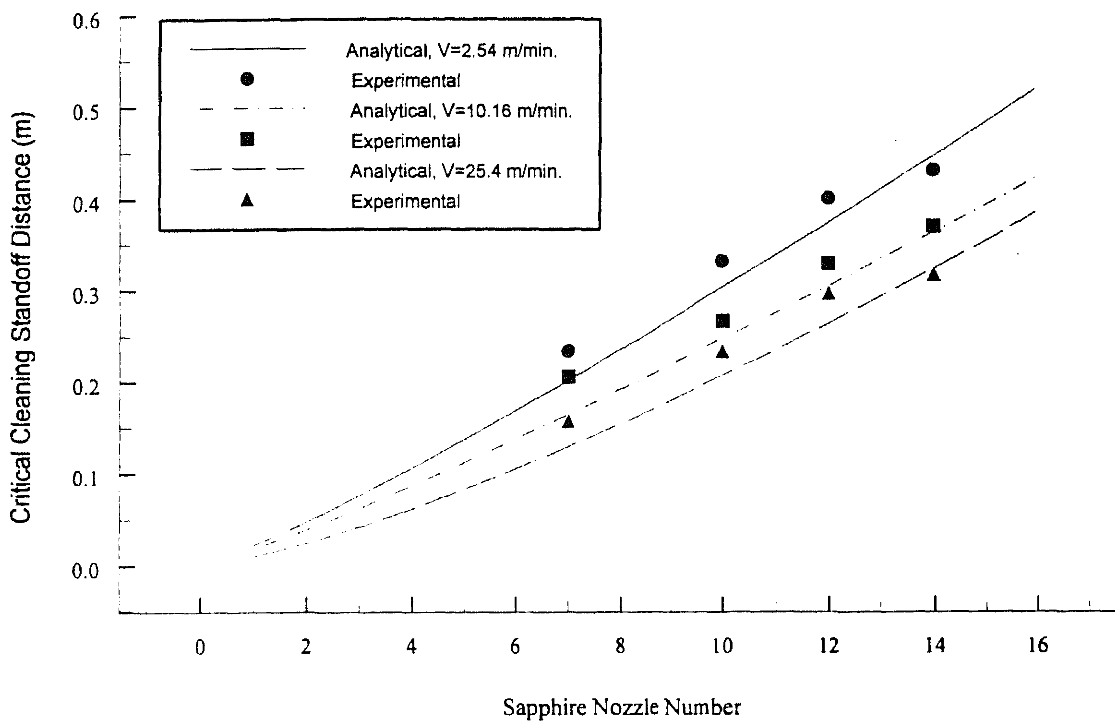

Fig. A.49 Critical cleaning standoff distance vs. nozzle number for epoxy-based paint removal at 276 MPa water pressure at three different travel speeds.

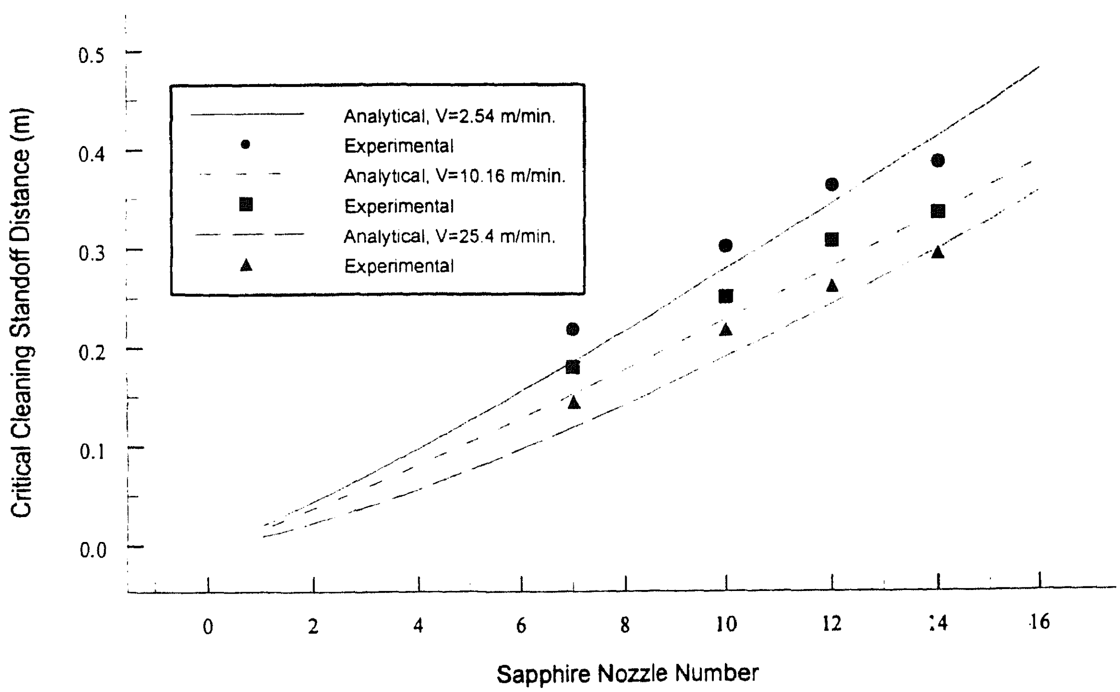

Fig. A.50 Critical cleaning standoff distance vs. nozzle number for epoxy-based paint removal at 207 MPa water pressure at three different travel speeds.

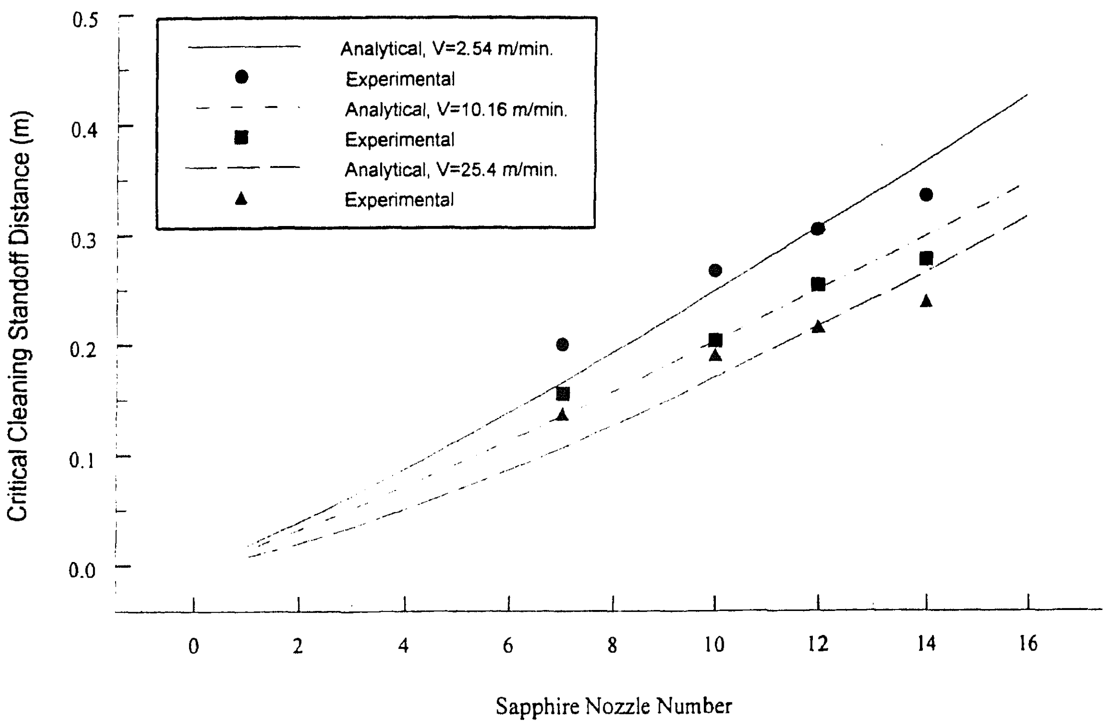

Fig. A.51 Critical cleaning standoff distance vs. nozzle number for epoxy-based paint removal at 138 MPa water pressure at three different travel speeds.

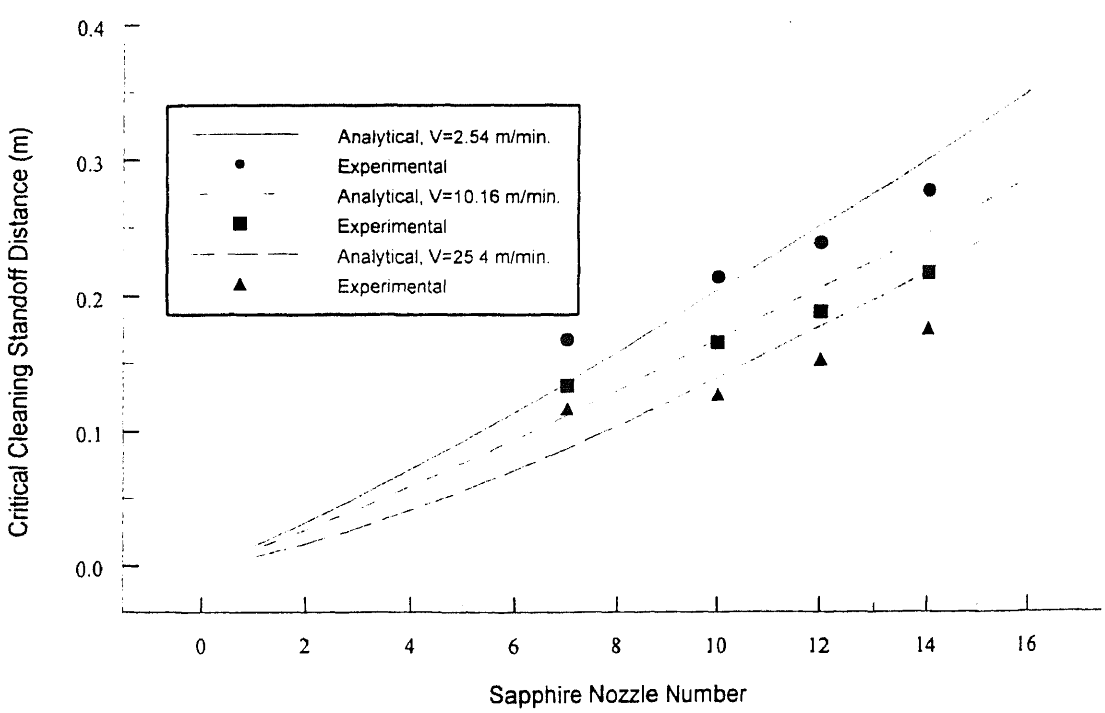

Fig. A.52 Critical cleaning standoff distance vs. nozzle number for epoxy-based paint removal at 69 MPa water pressure at three different travel speeds.

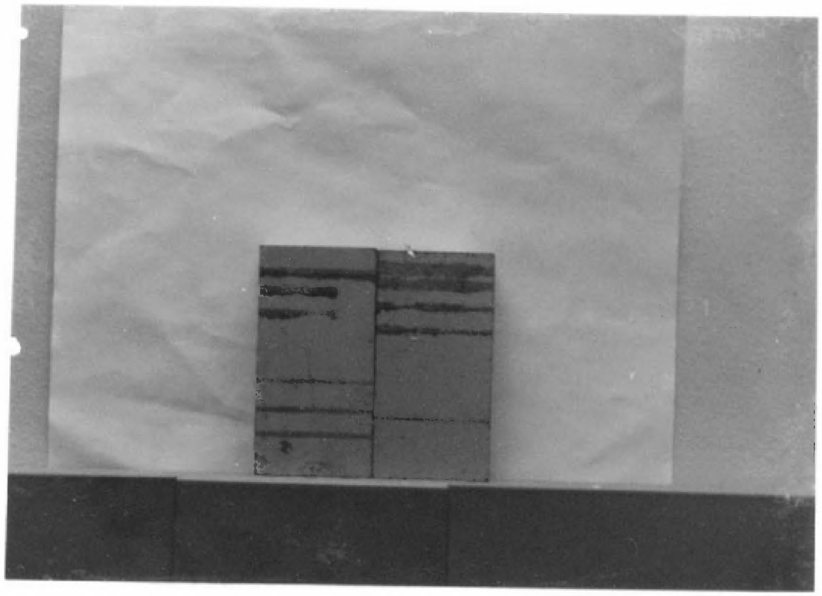

Fig. A.53 Comparison of epoxy-based paint removal with and without surfactant FC-722 pretreatment on coating (nozzle no. 14, focusing tube no. 63, 172 MPa water pressure and travel speed of 10.16 m/min. difference in up and bottom part of right sample).

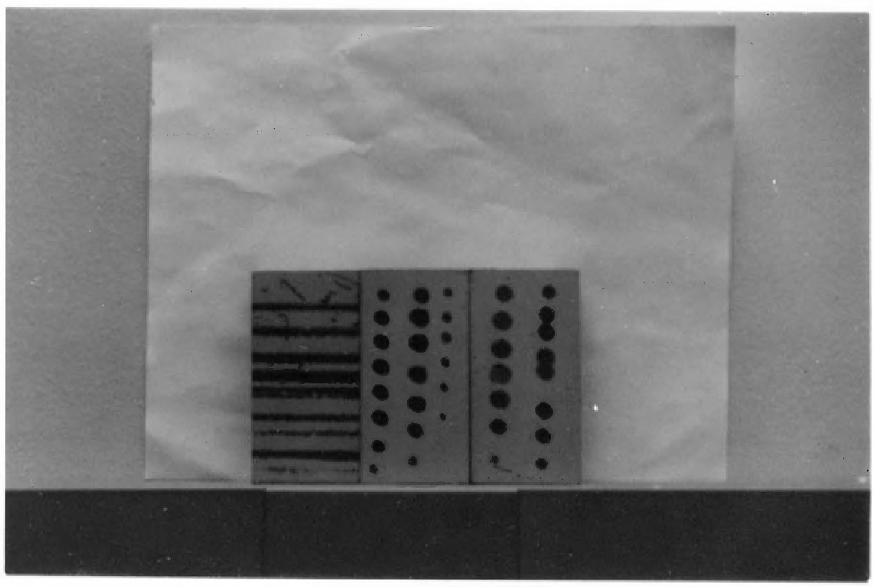

Fig. A.54 Correlation between cleaning width and the standoff distance (left sample was made by moving jet, and right two samples were made by stationary jet).

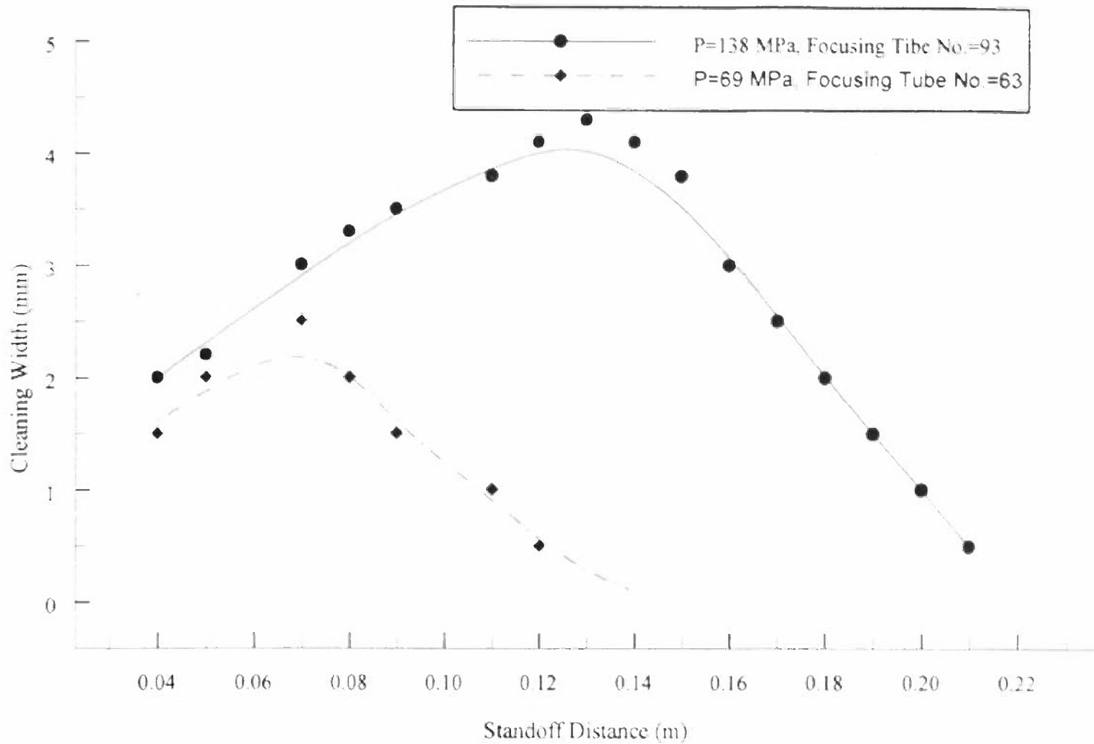

Fig. A.55 Cleaning width vs. standoff distance for oil-based paint removal with the modified nozzle body, nozzle 12 and focusing tubes at travel speed of 10.16 m/min. and two different water pressures.

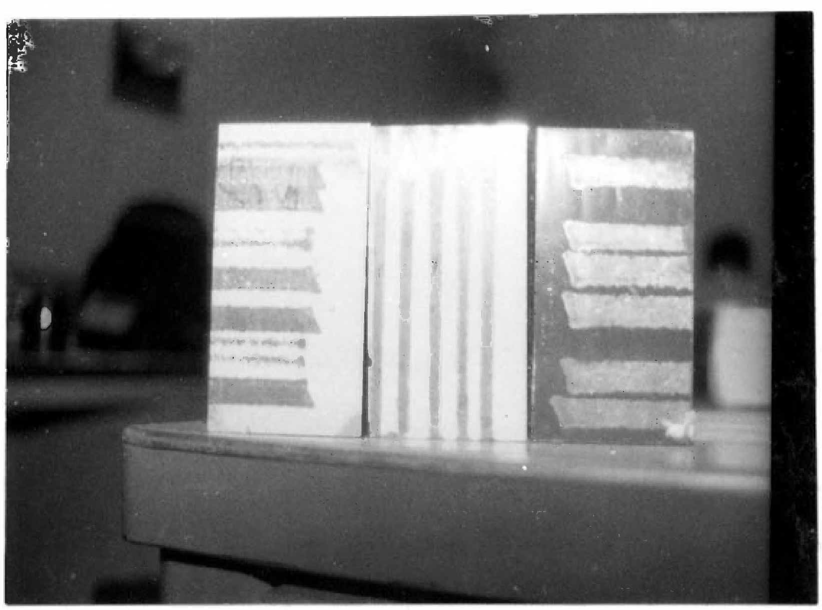

Fig. A.56 Comparison in cleaning width by the use of spiral and modified nozzle body (the left and right samples were made by using the spiral nozzle body, the middle one was made by using the modified nozzle body).

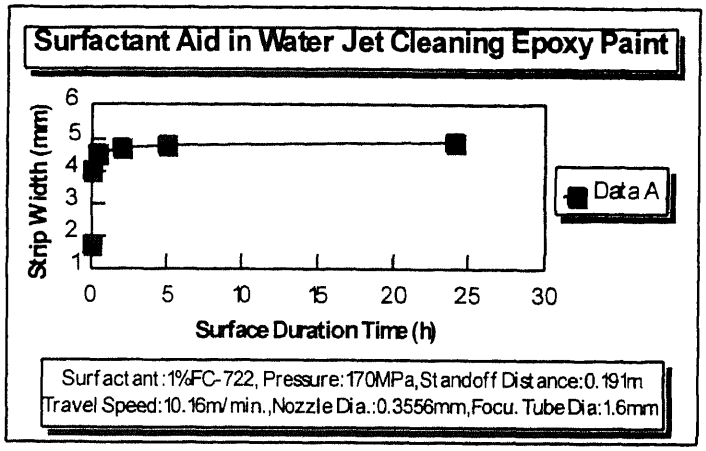

Fig. A.57 Cleaning width vs. duration of effect of surfactant.

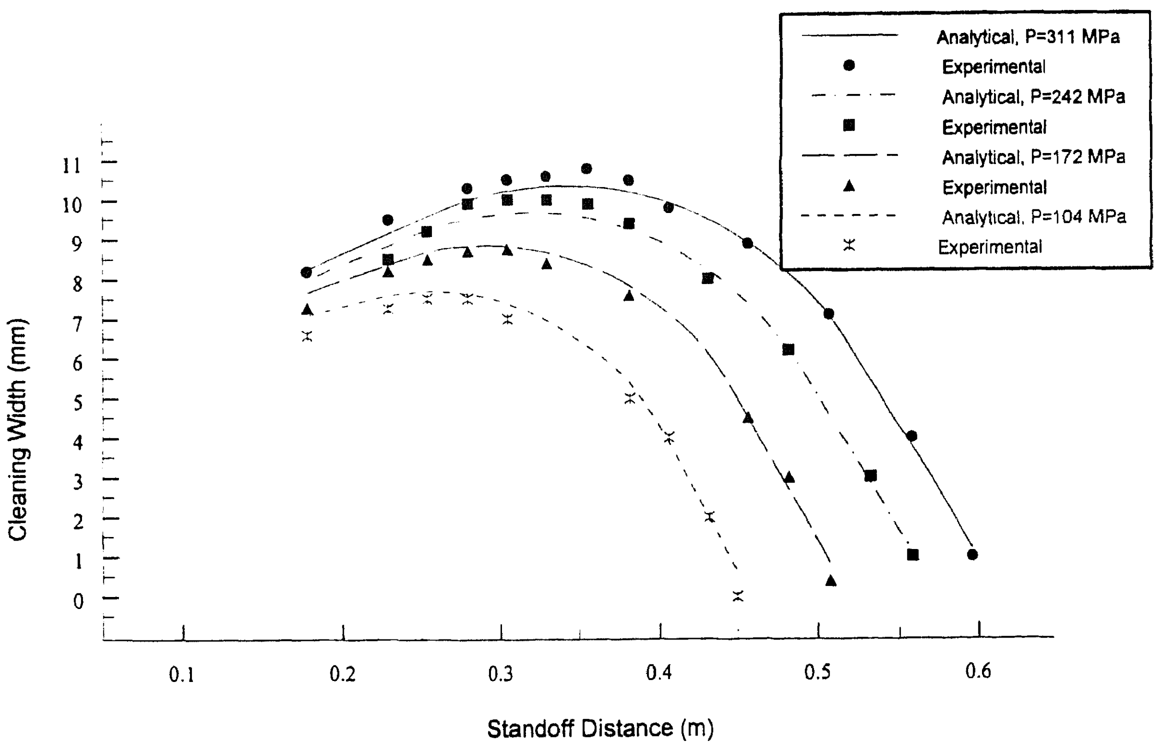

Fig. A.58 Cleaning width vs. standoff distance for stationary jet oil-based paint removal with nozzle no. 14 under four different water pressures.

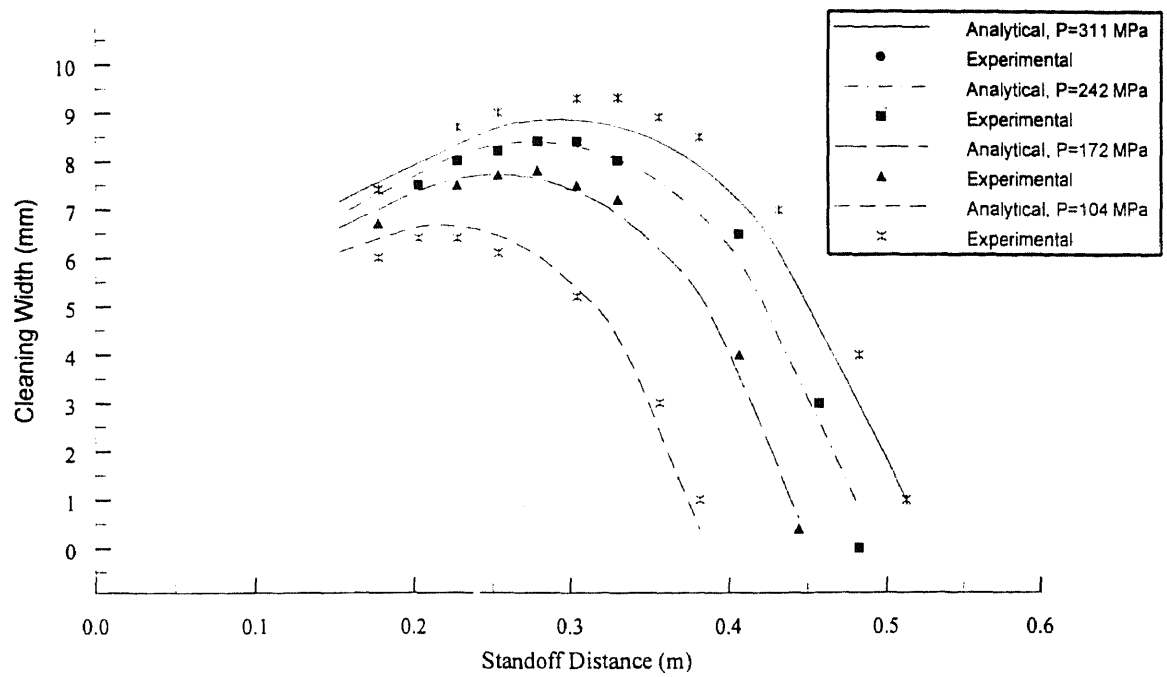

Fig. A.59 Cleaning width vs. standoff distance for stationary jet oil-based paint removal with nozzle no. 12 under four different water pressures.

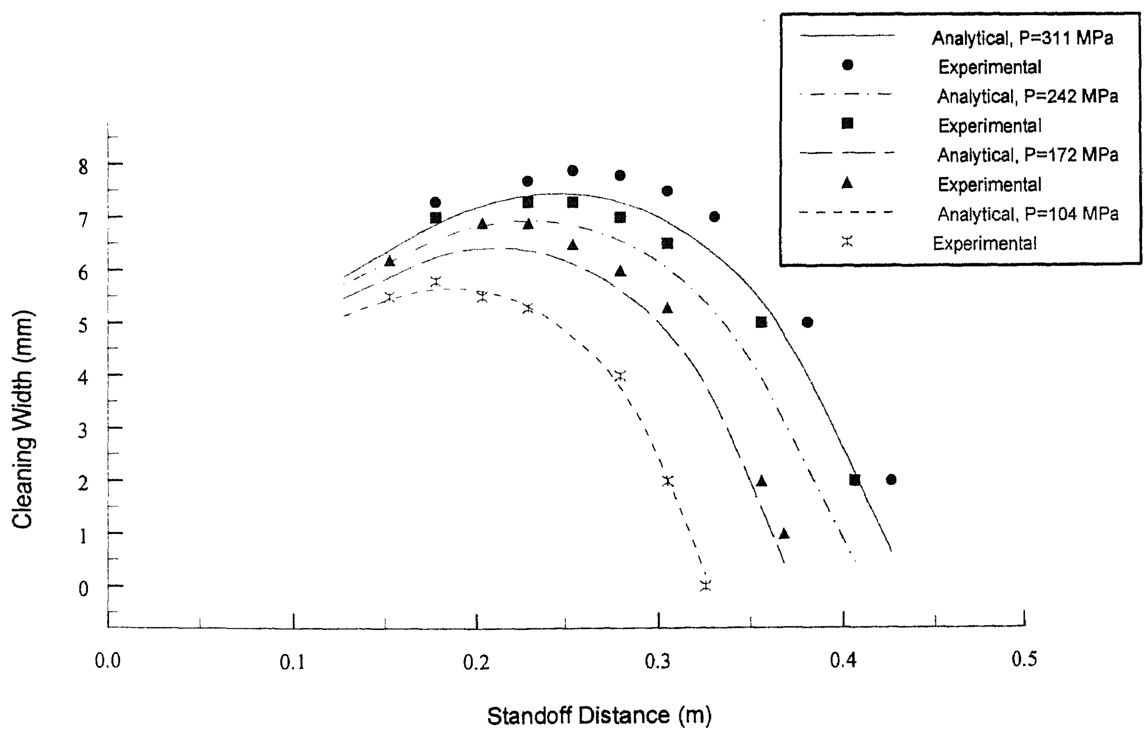

Fig. A.60 Cleaning width vs. standoff distance for stationary jet oil-based paint removal with nozzle no. 10 under four different water pressures.

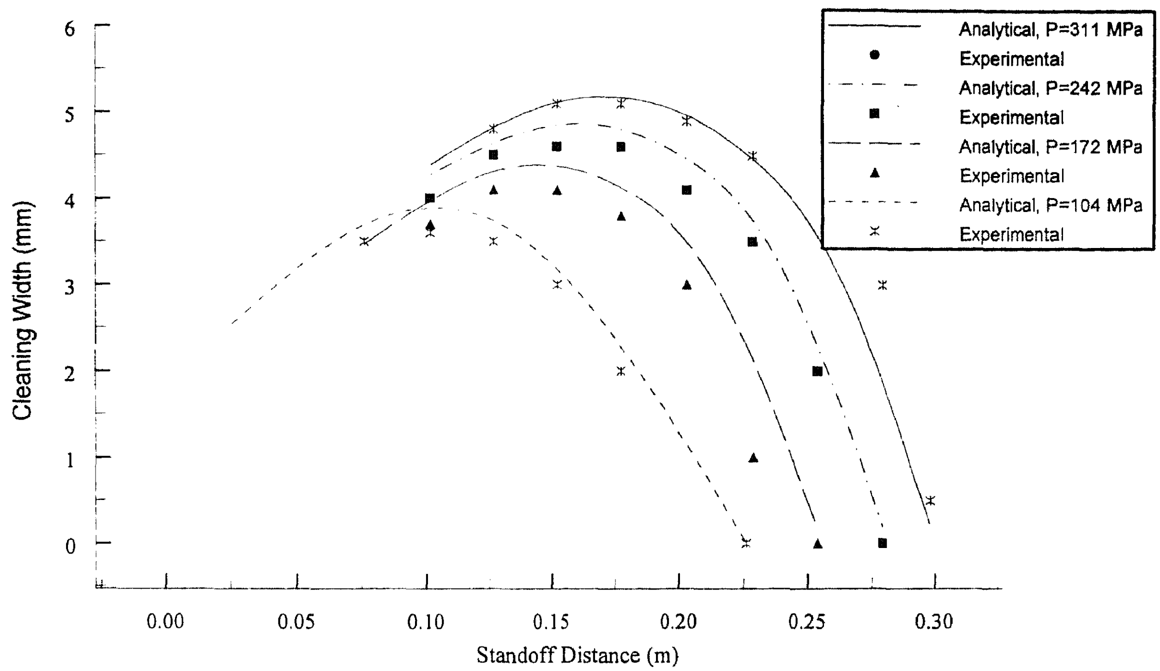

Fig. A.61 Cleaning width vs. standoff distance for stationary jet oil-based paint removal with nozzle no. 7 under four different water pressures.

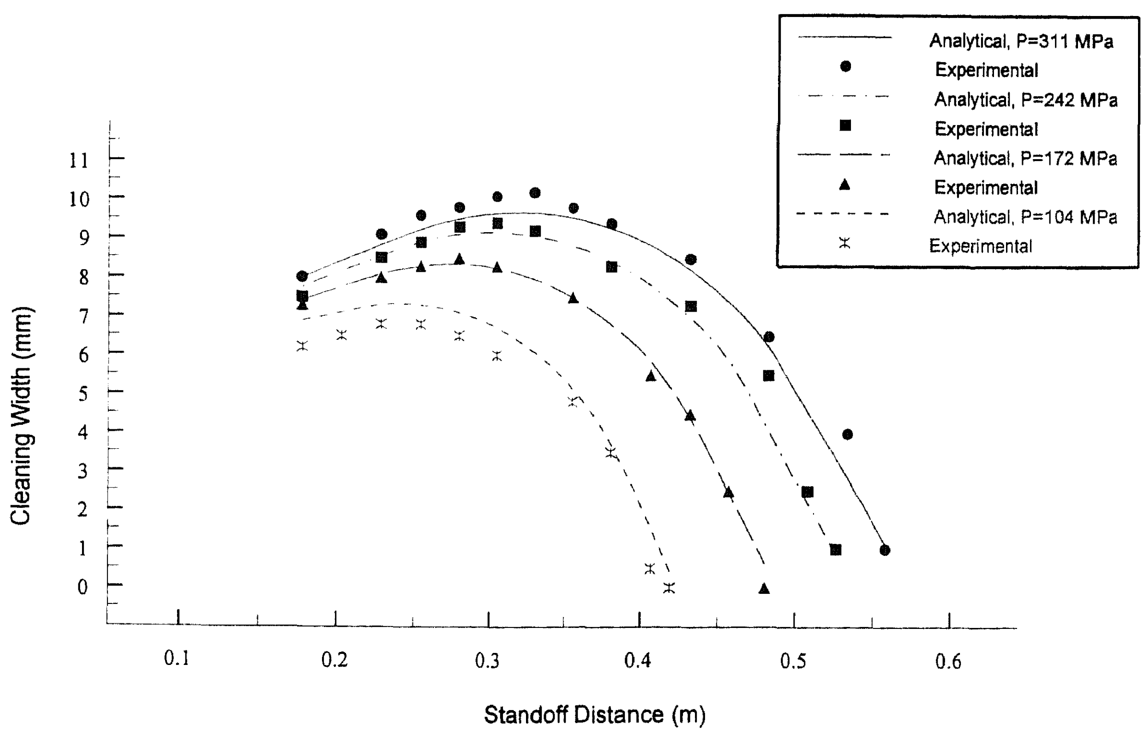

Fig. A.62 Cleaning width vs. standoff distance for stationary jet epoxy-based paint removal with nozzle no. 14 under four different water pressures.

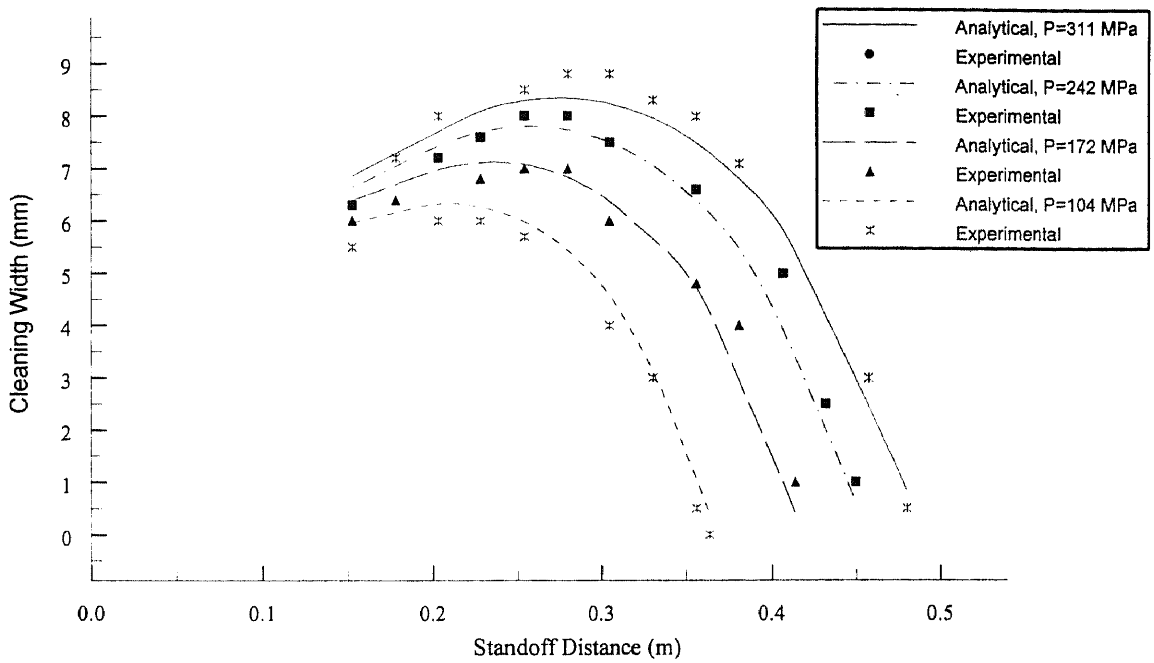

Fig. A.63 Cleaning width vs. standoff distance for stationary jet epoxy-based paint removal with nozzle no. 12 under four different water pressures.

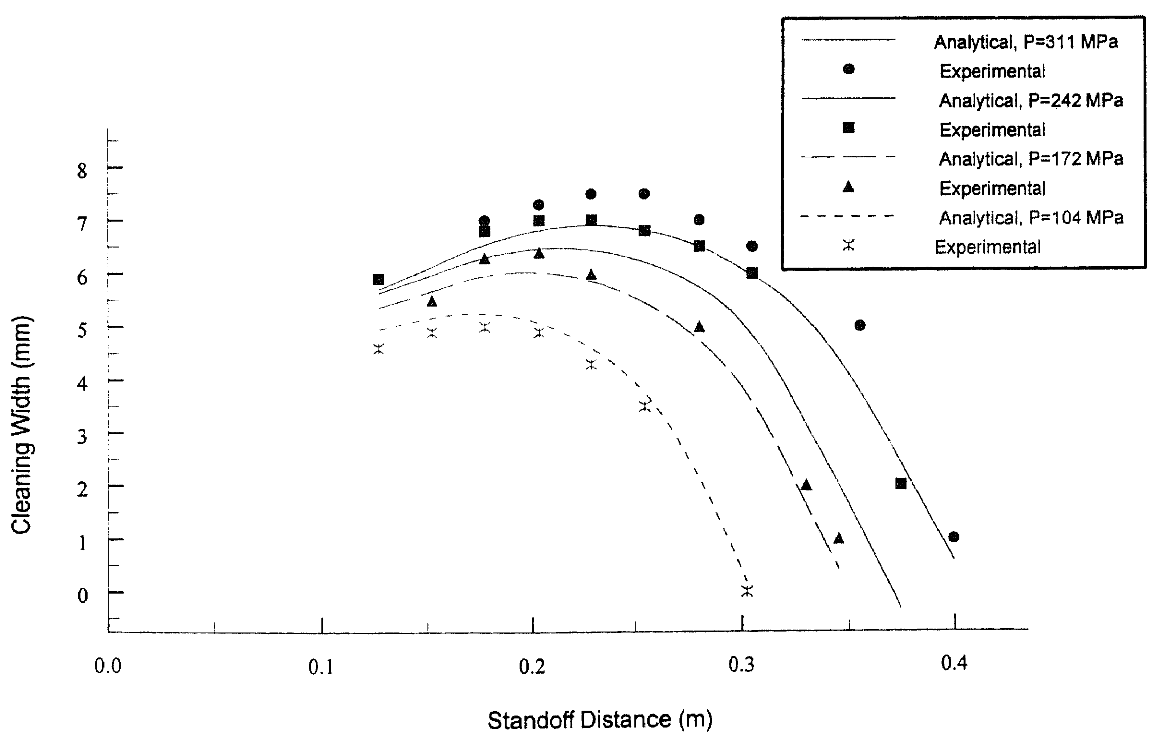

Fig. A.64 Cleaning width vs. standoff distance for stationary jet epoxy-based paint removal with nozzle no. 10 under four different water pressures.

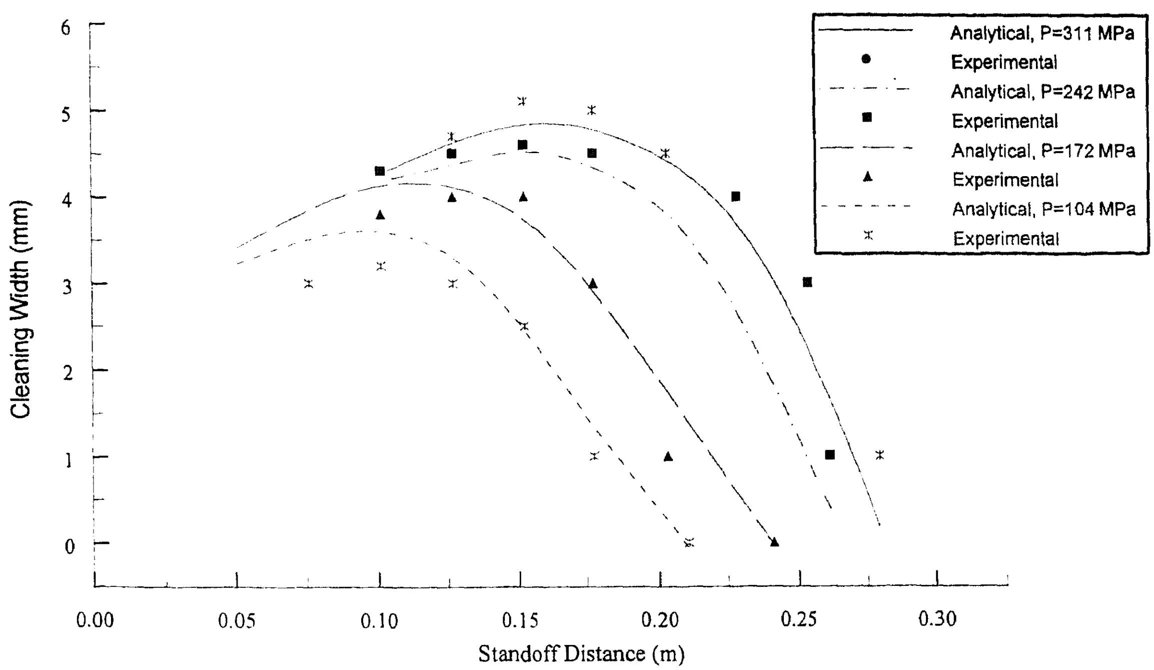

Fig. A.65 Cleaning width vs. standoff distance for stationary jet epoxy-based paint removal with nozzle no. 7 under four different water pressures.

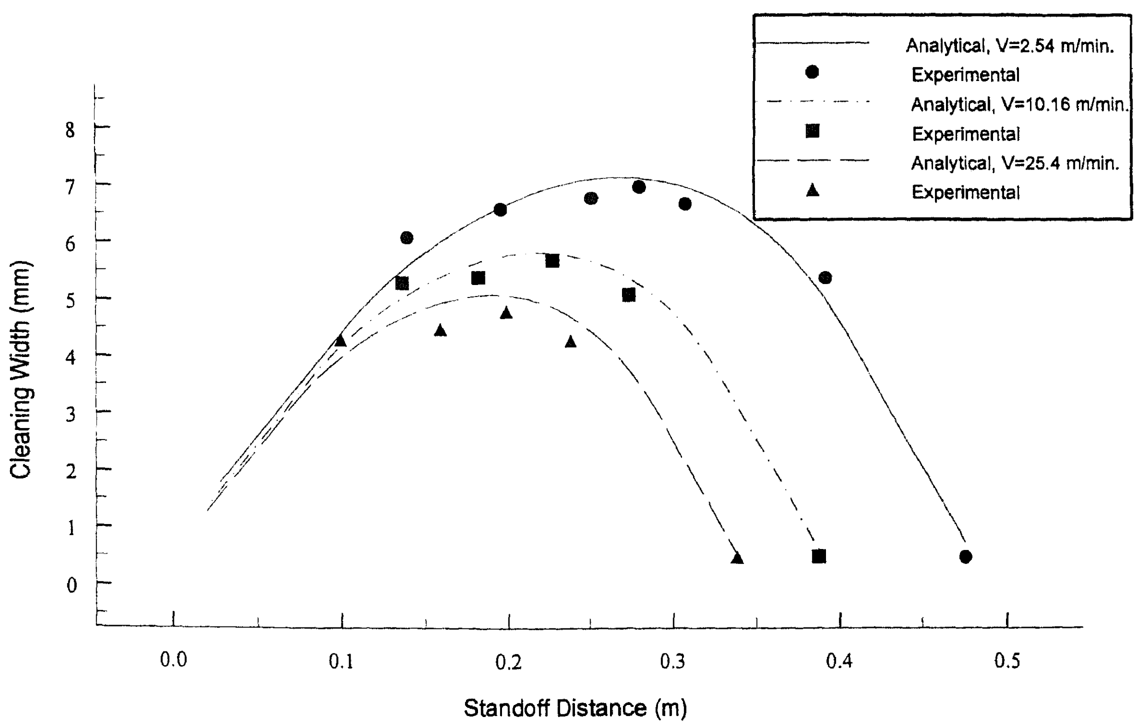

Fig. A.66 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 14 at 276 MPa and three different travel speeds.

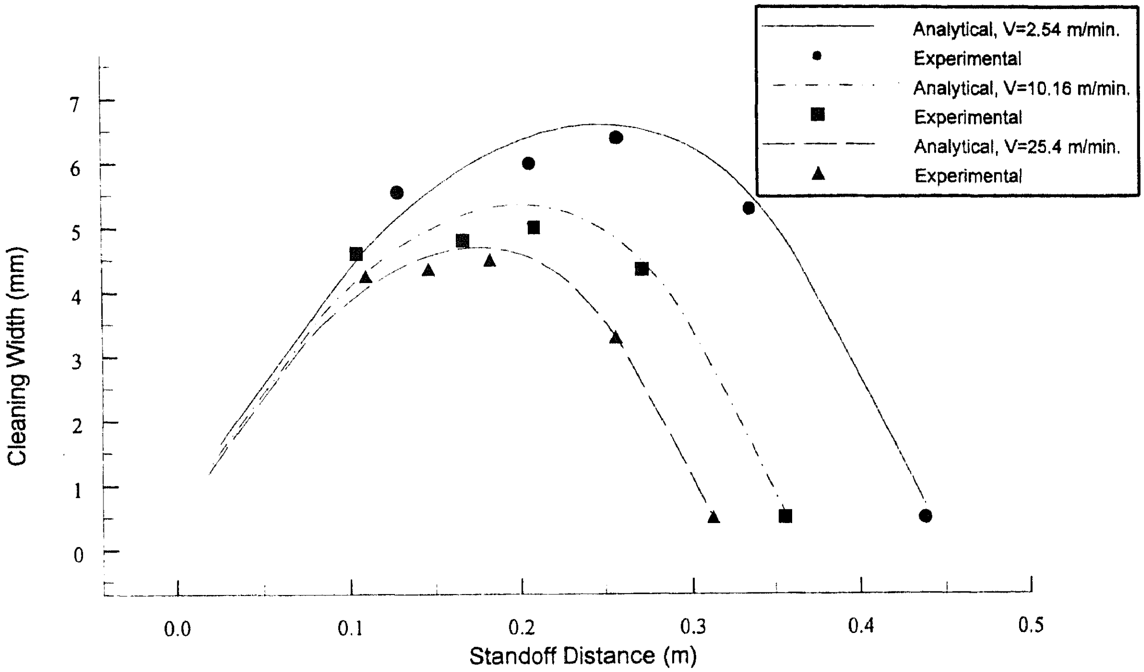

Fig. A.67 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 14 at 207 MPa and three different travel speeds.

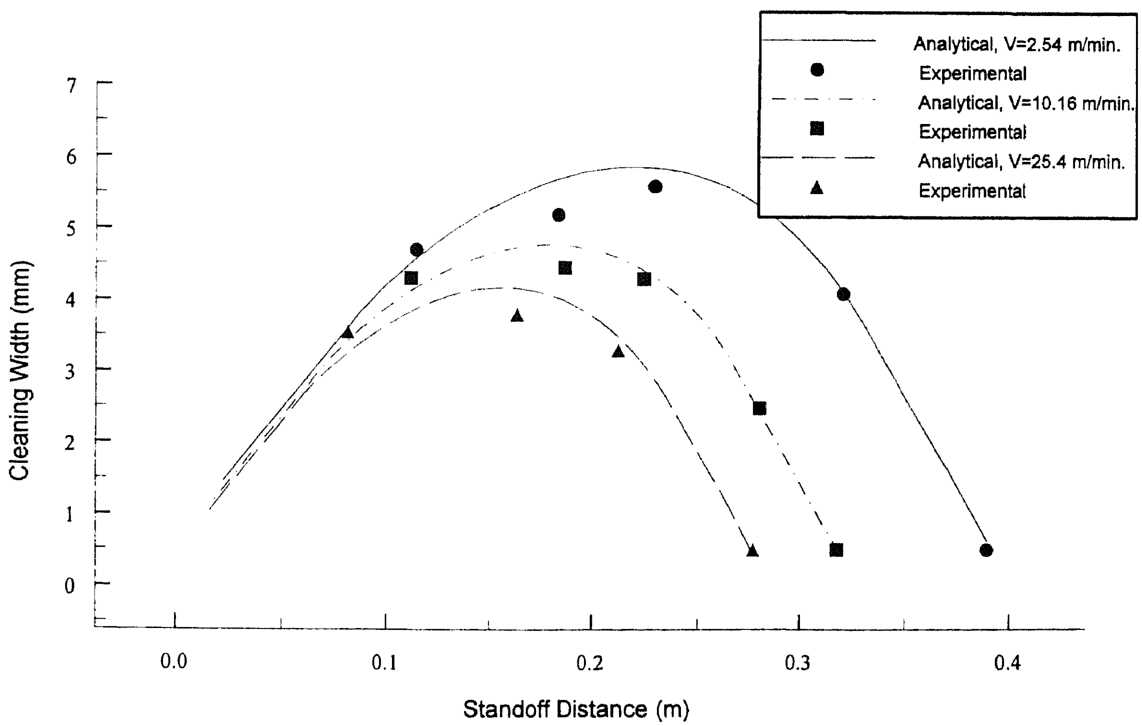

Fig. A.68 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 14 at 138 MPa and three different travel speeds.

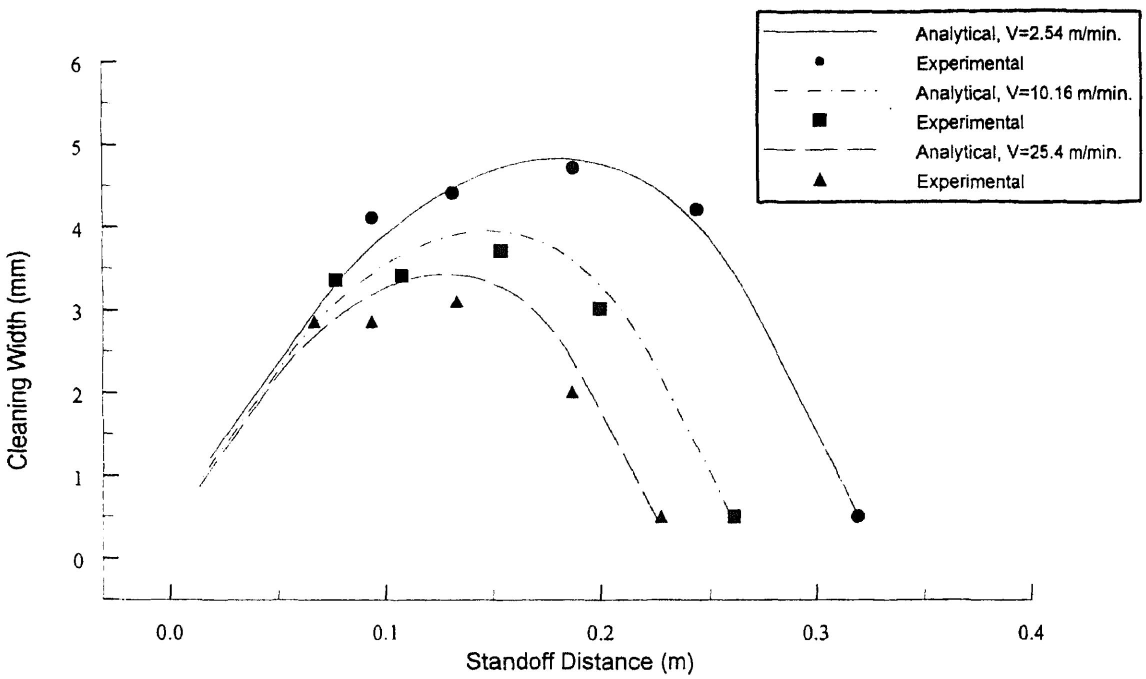

Fig. A.69 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 14 at 69 MPa and three different travel speeds.

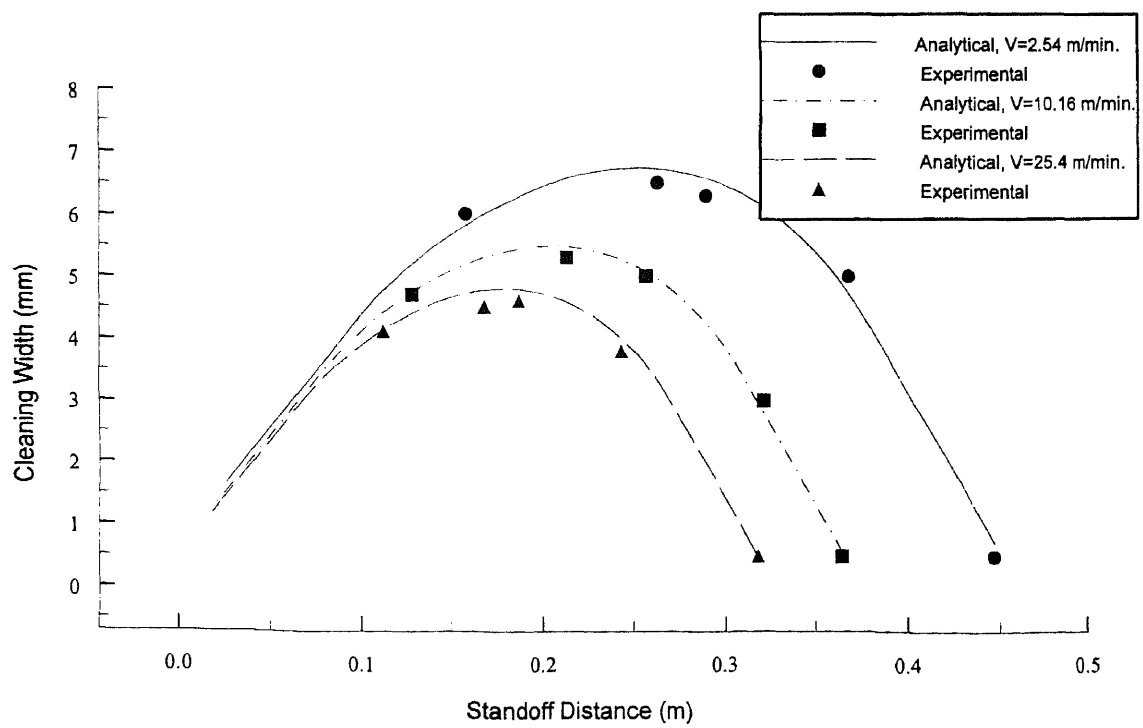

Fig. A.70 Cleaning width vs. standoff distance for moving jet epoxy-based paint removal with nozzle no. 14 at 276 MPa and three different travel speeds.

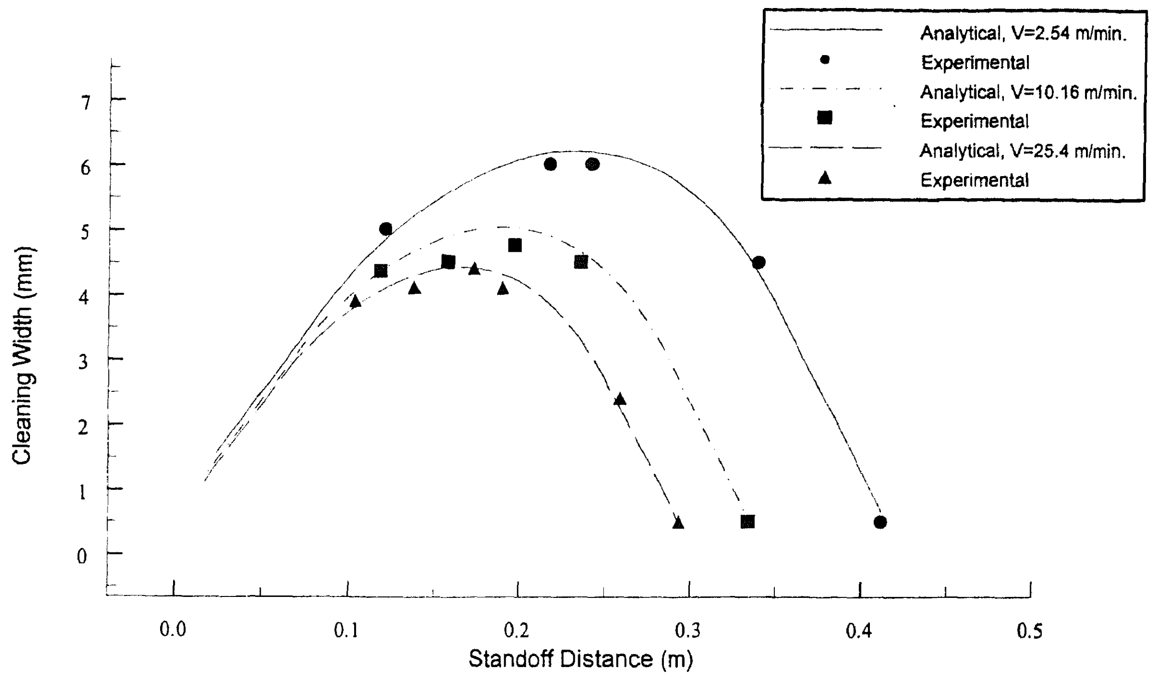

Fig. A.71 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 14 at 207 MPa and three different travel speeds.

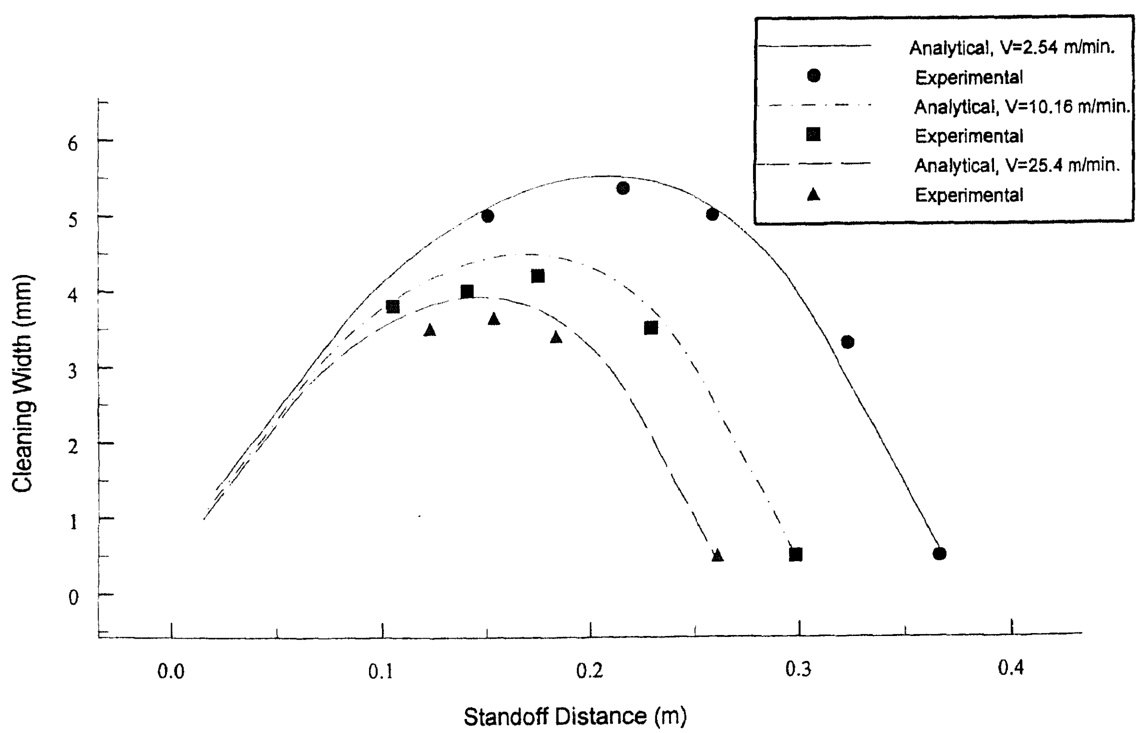

Fig. A.72 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 14 at 138 MPa and three different travel speeds.

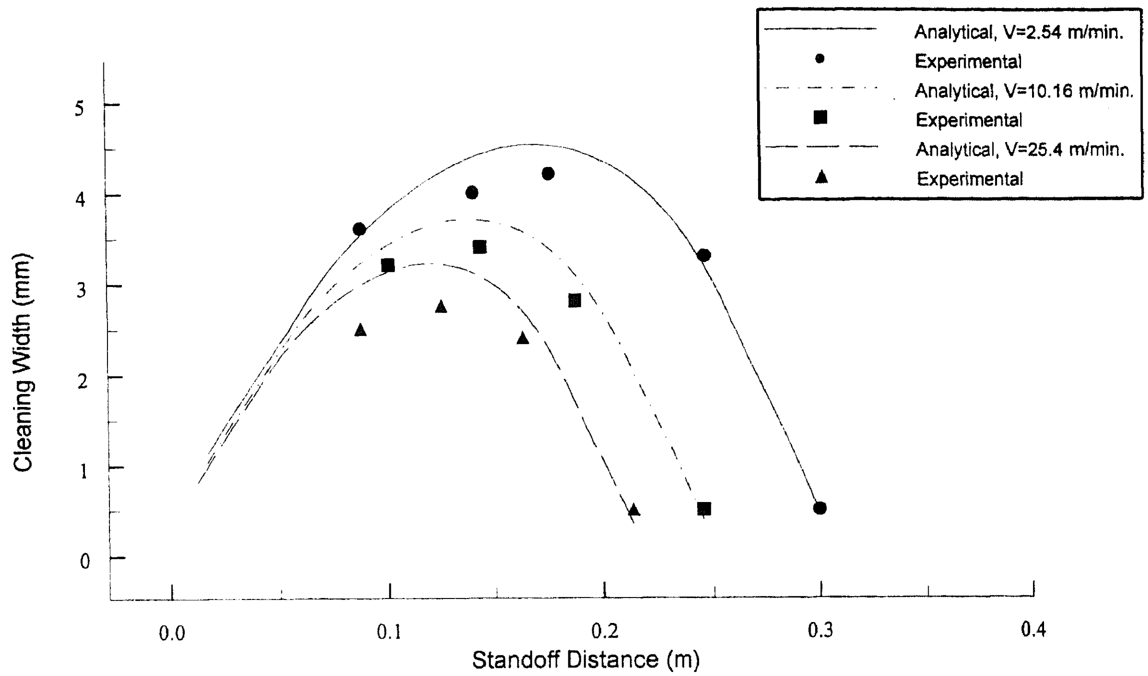

Fig. A.73 Cleaning width vs. standoff distance for moving epoxy oil-based paint removal with nozzle no. 14 at 69 MPa and three different travel speeds.

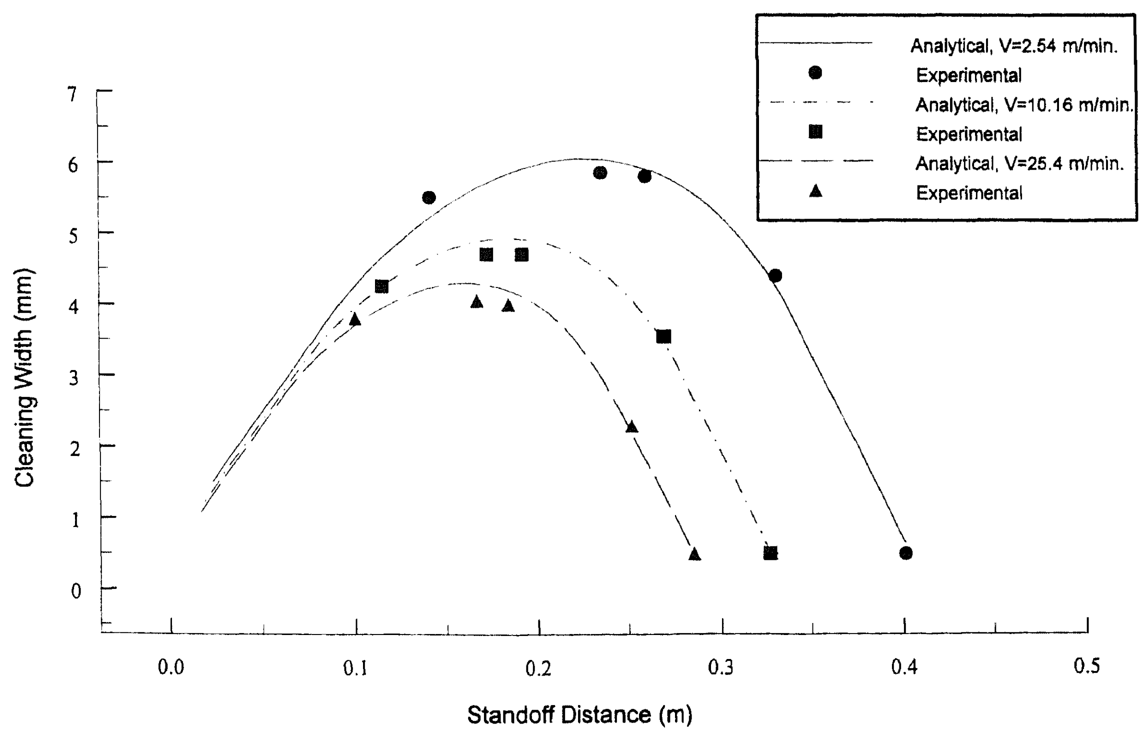

Fig. A.74 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 12 at 276 MPa and three different travel speeds.

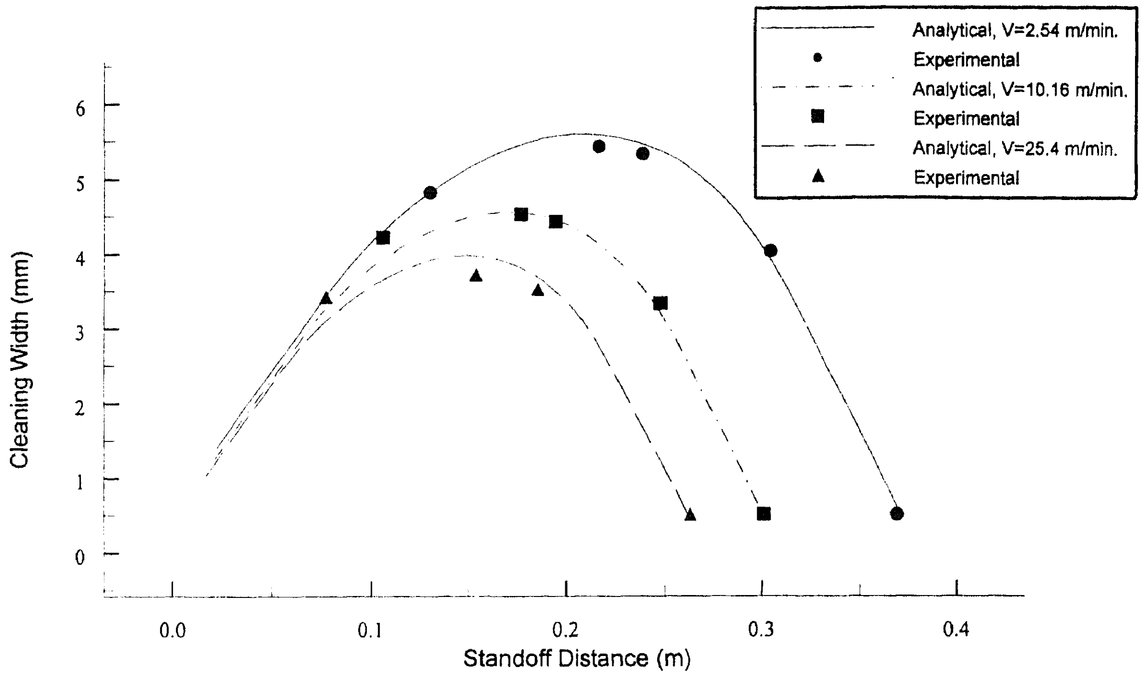

Fig. A.75 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 12 at 207 MPa and three different travel speeds.

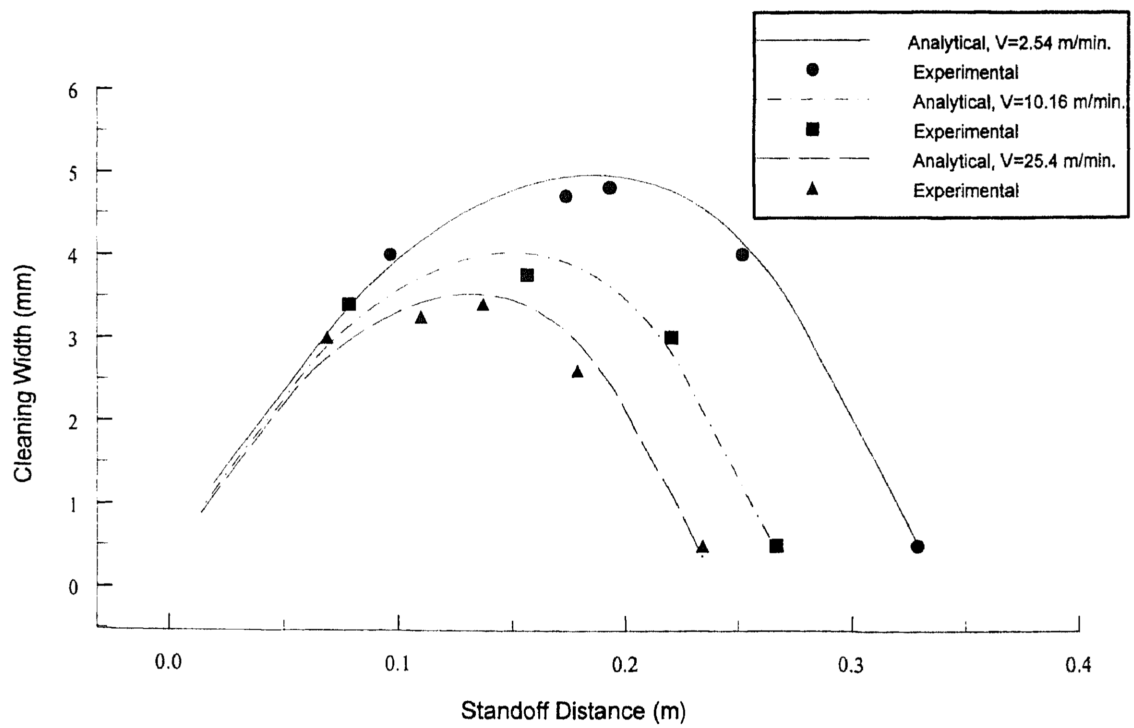

Fig. A.76 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 12 at 138 MPa and three different travel speeds.

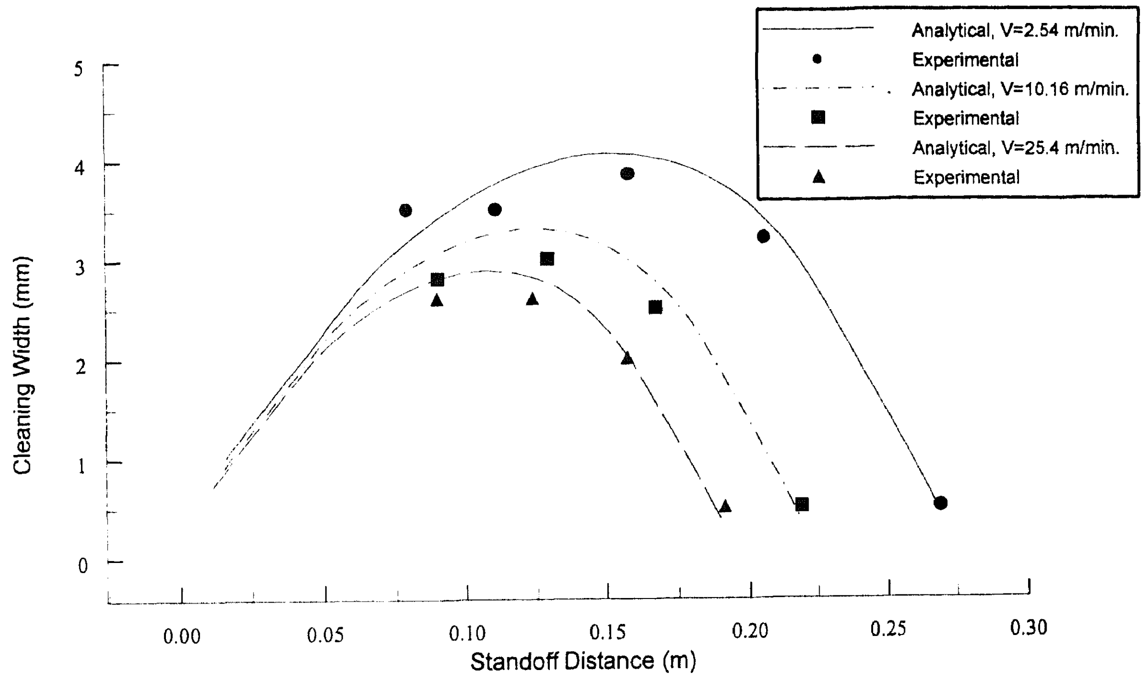

Fig. A.77 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 12 at 69 MPa and three different travel speeds.

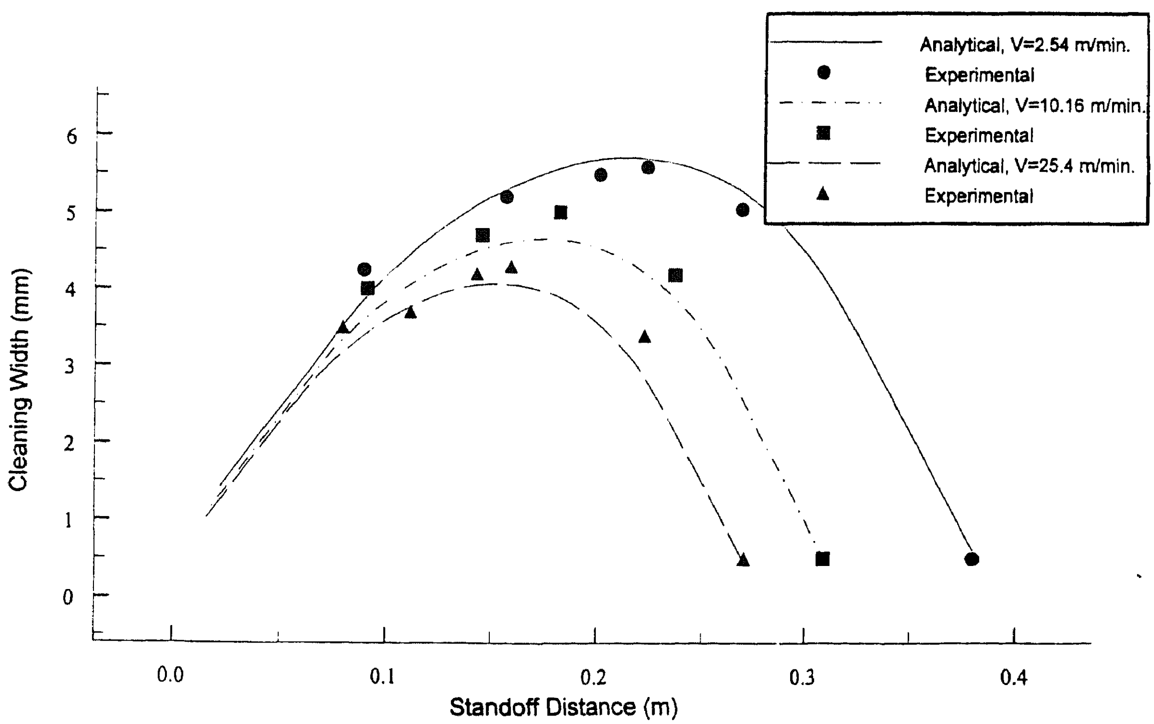

Fig. A.78 Cleaning width vs. standoff distance for moving jet epoxy-based paint removal with nozzle no. 12 at 276 MPa and three different travel speeds.

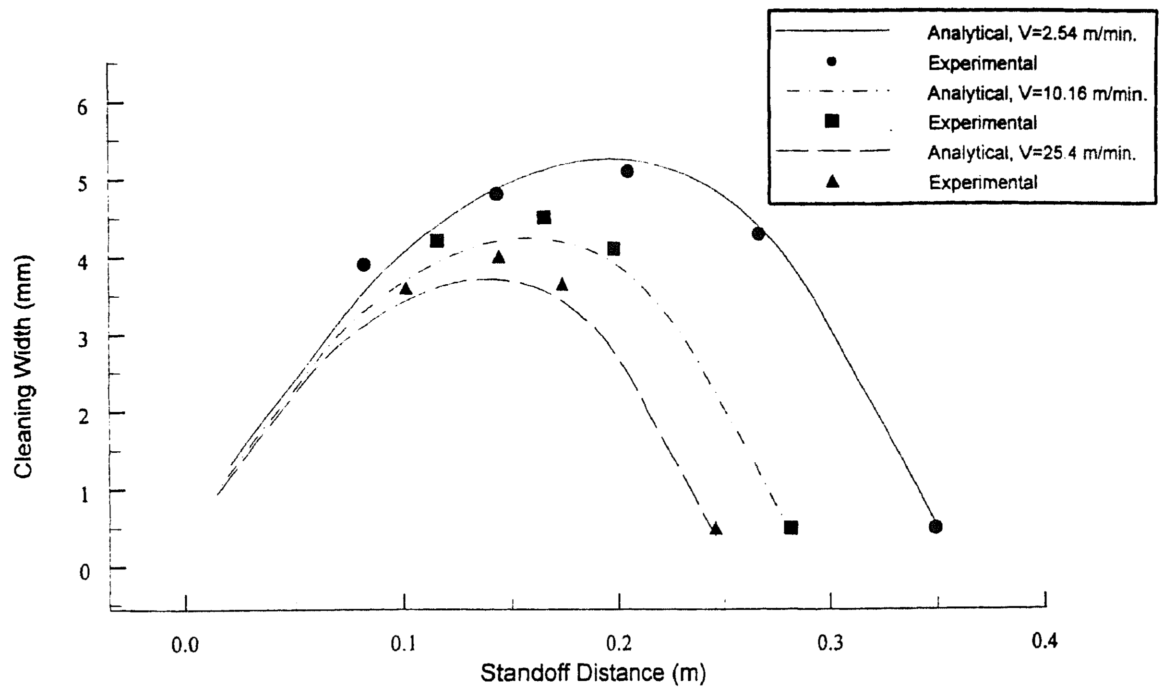

Fig. A.79 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 12 at 207 MPa and three different travel speeds.

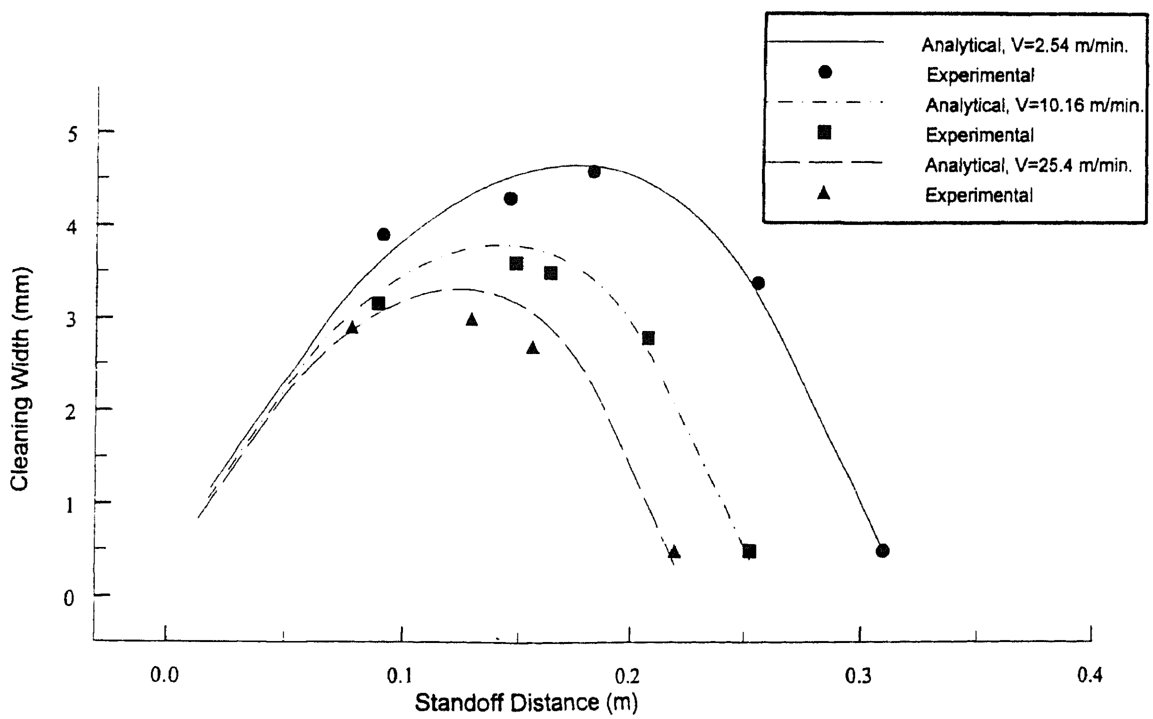

Fig. A.80 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 12 at 138 MPa and three different travel speeds.

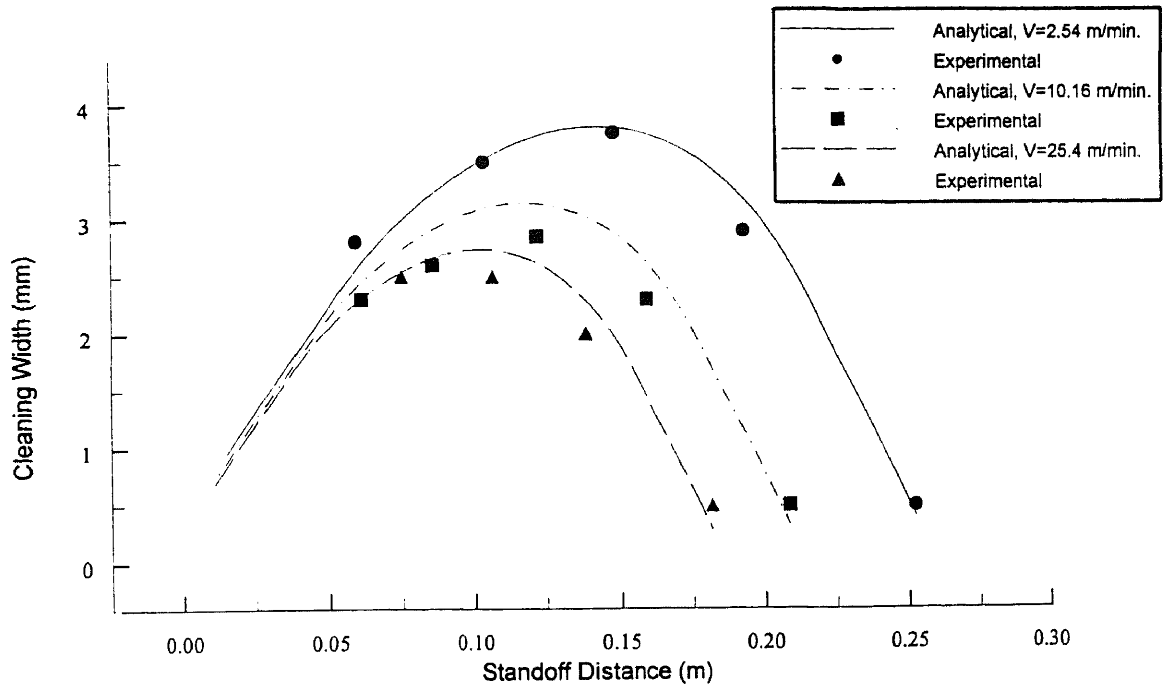

Fig. A.81 Cleaning width vs. standoff distance for moving epoxy oil-based paint removal with nozzle no. 12 at 69 MPa and three different travel speeds.

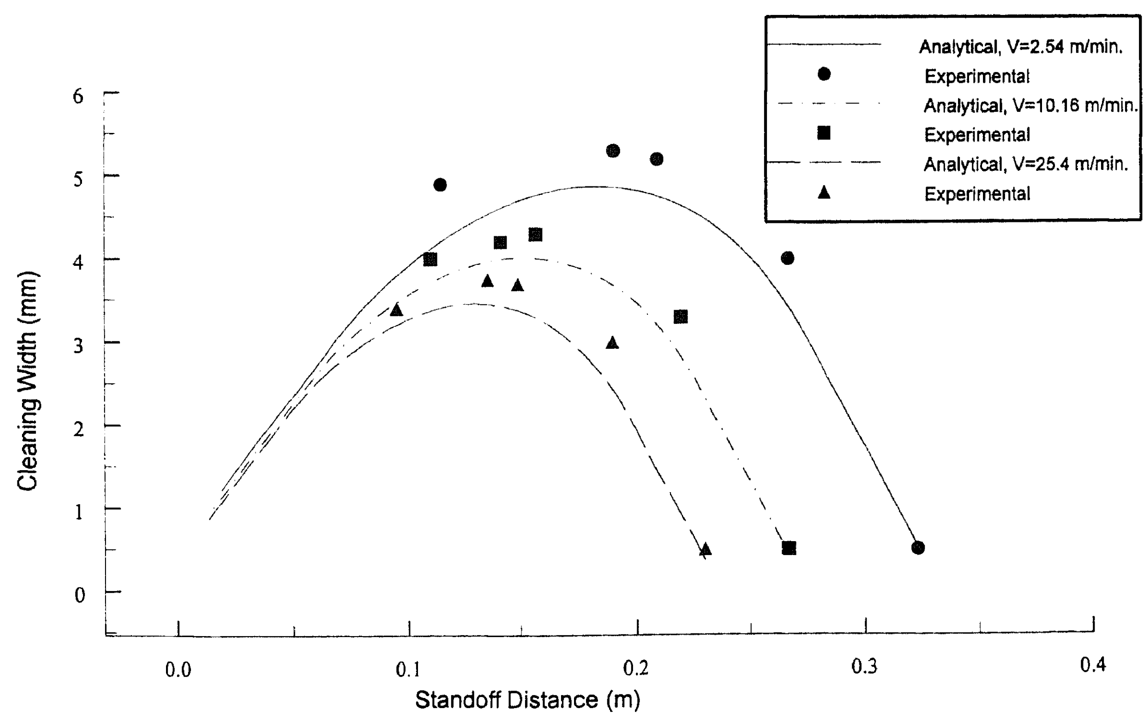

Fig. A.82 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 10 at 276 MPa and three different travel speeds.

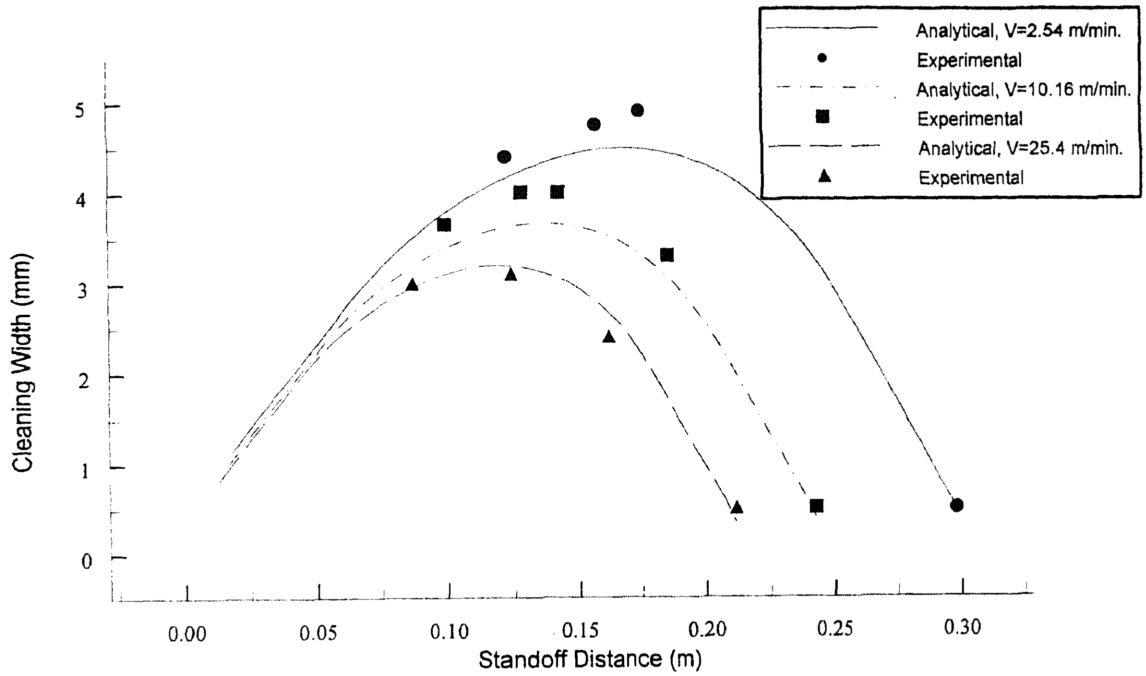

Fig. A.83 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 10 at 207 MPa and three different travel speeds.

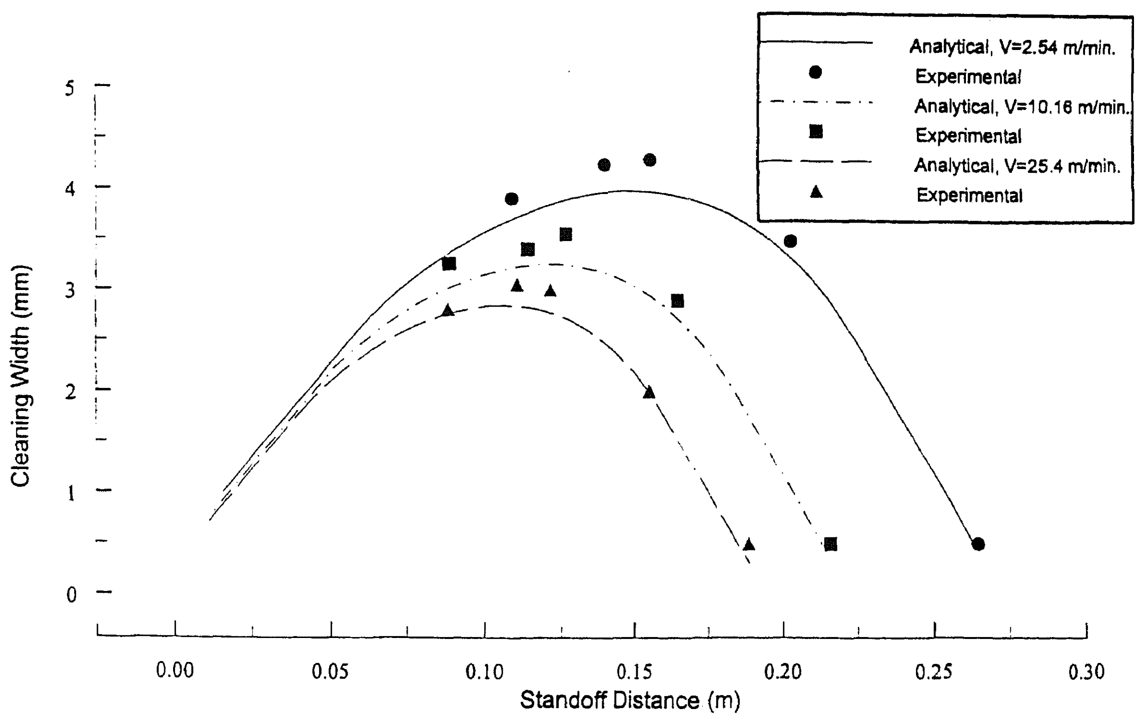

Fig. A.84 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no 10. at 138 MPa and three different travel speeds.

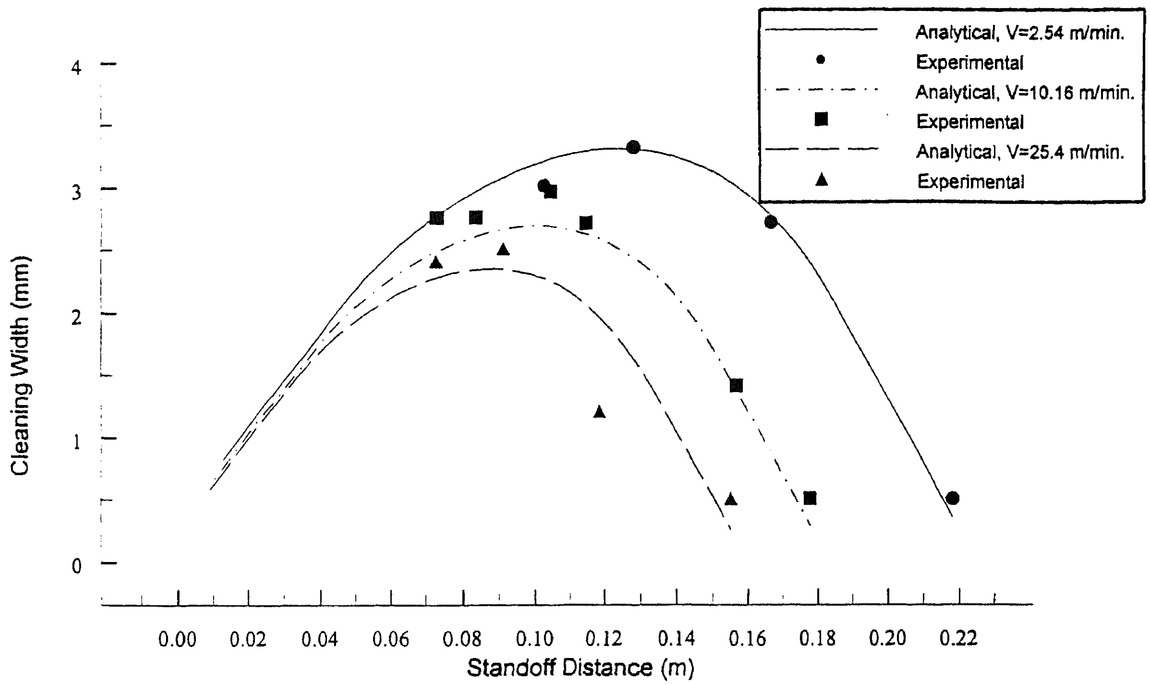

Fig. A.85 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 10 at 69 MPa and three different travel speeds.

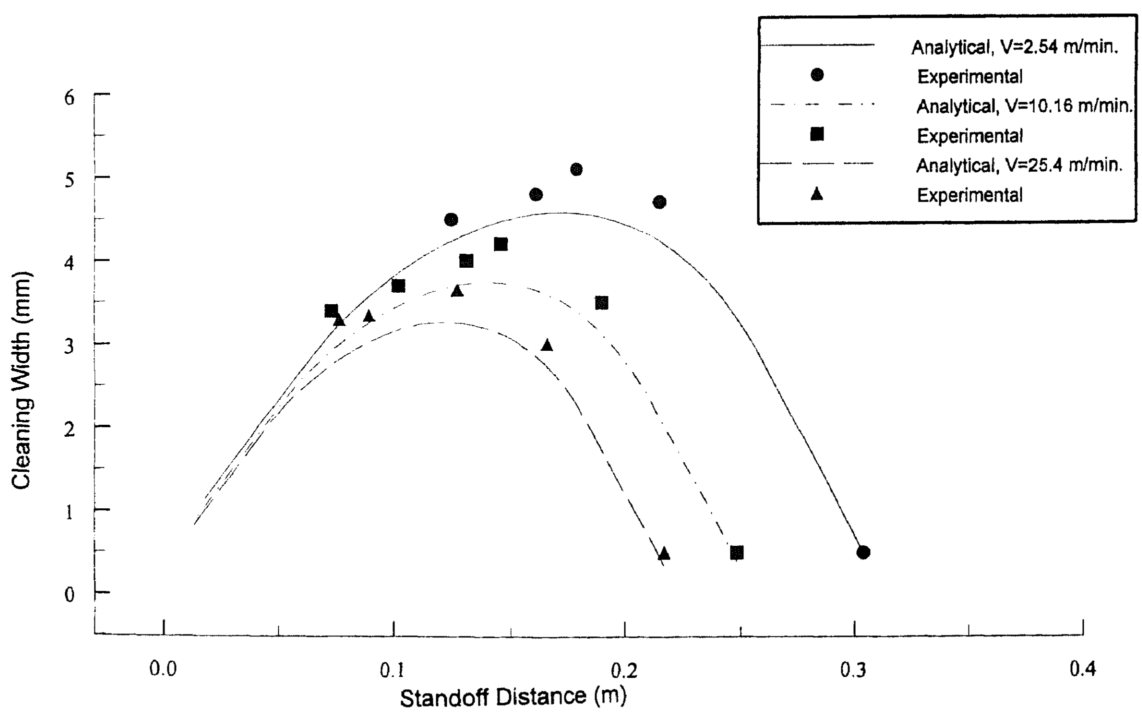

Fig. A.86 Cleaning width vs. standoff distance for moving jet epoxy-based paint removal with nozzle no. 10 at 276 MPa and three different travel speeds.

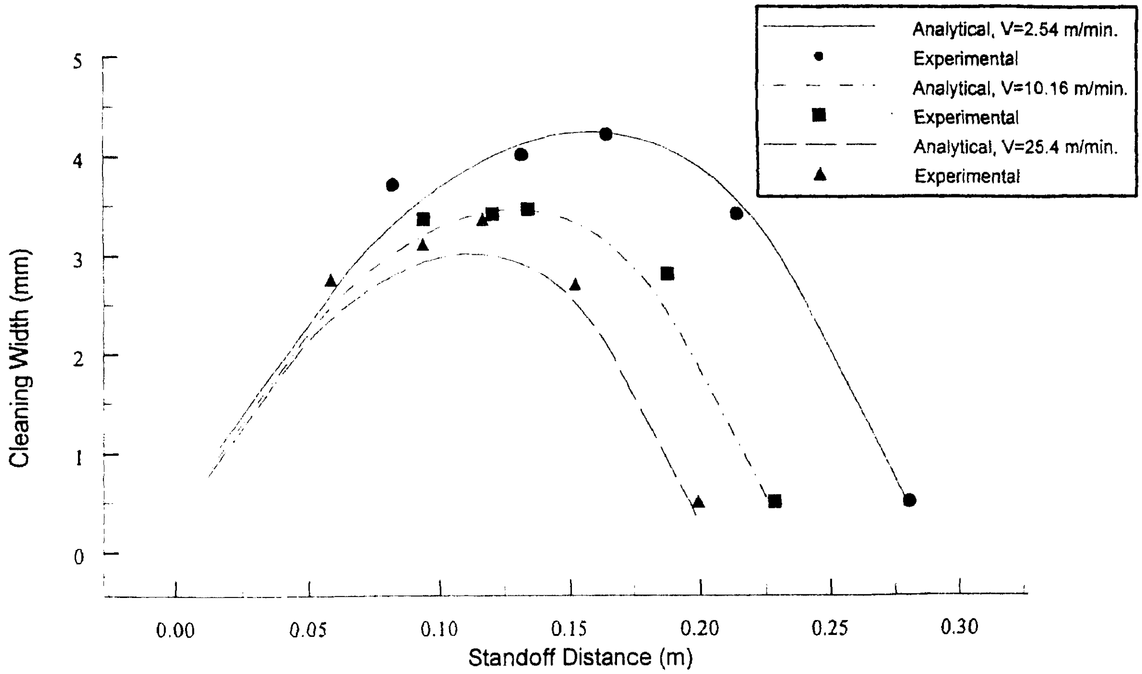

Fig. A.87 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 10 at 207 MPa and three different travel speeds.

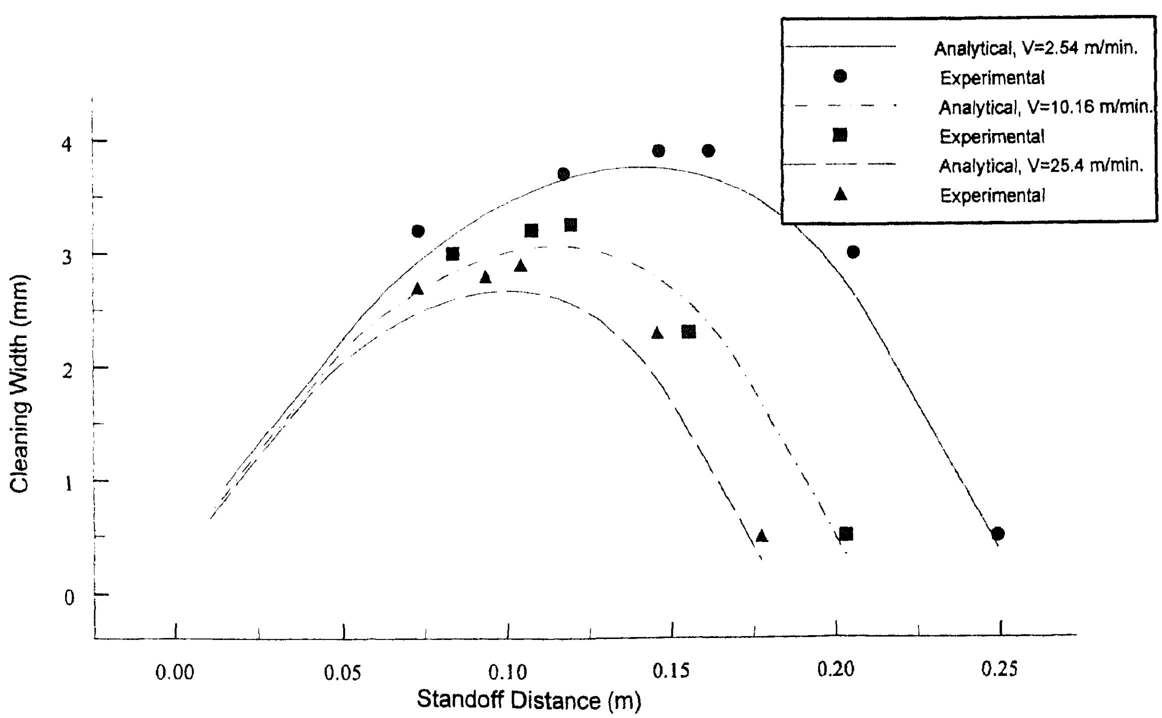

Fig. A.88 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 10 at 138 MPa and three different travel speeds.

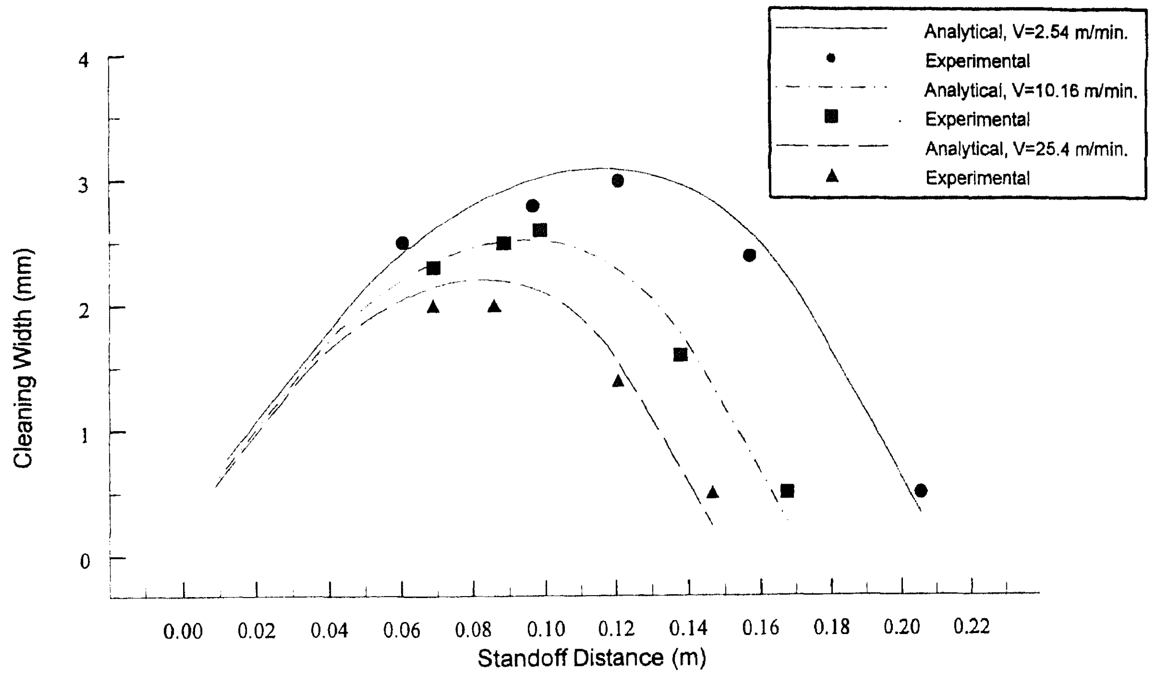

Fig. A.89 Cleaning width vs. standoff distance for moving epoxy oil-based paint removal with nozzle no. 10 at 69 MPa and three different travel speeds.

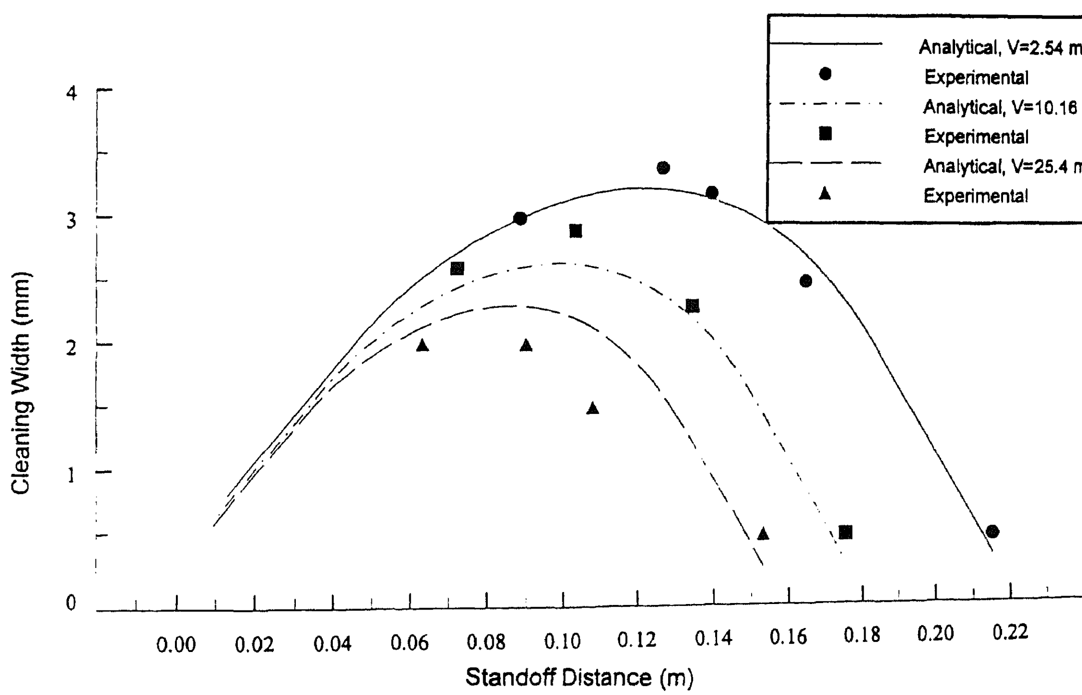

Fig. A.90 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 7 at 276 MPa and three different travel speeds.

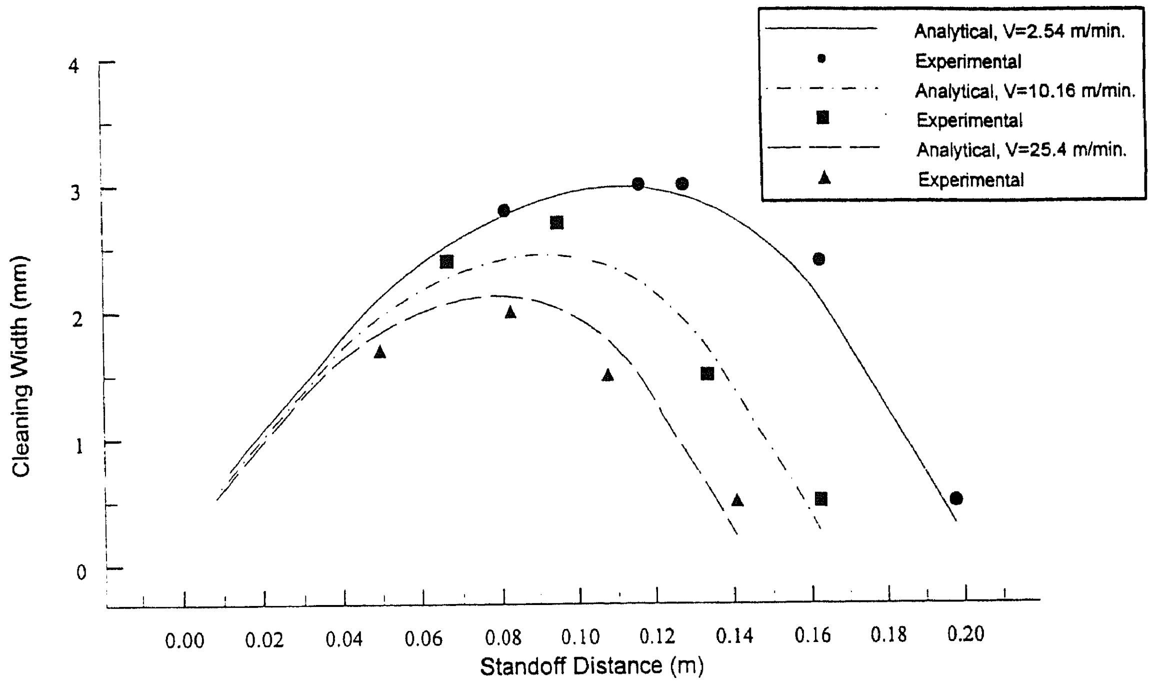

Fig. A.91 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 7 at 207 MPa and three different travel speeds.

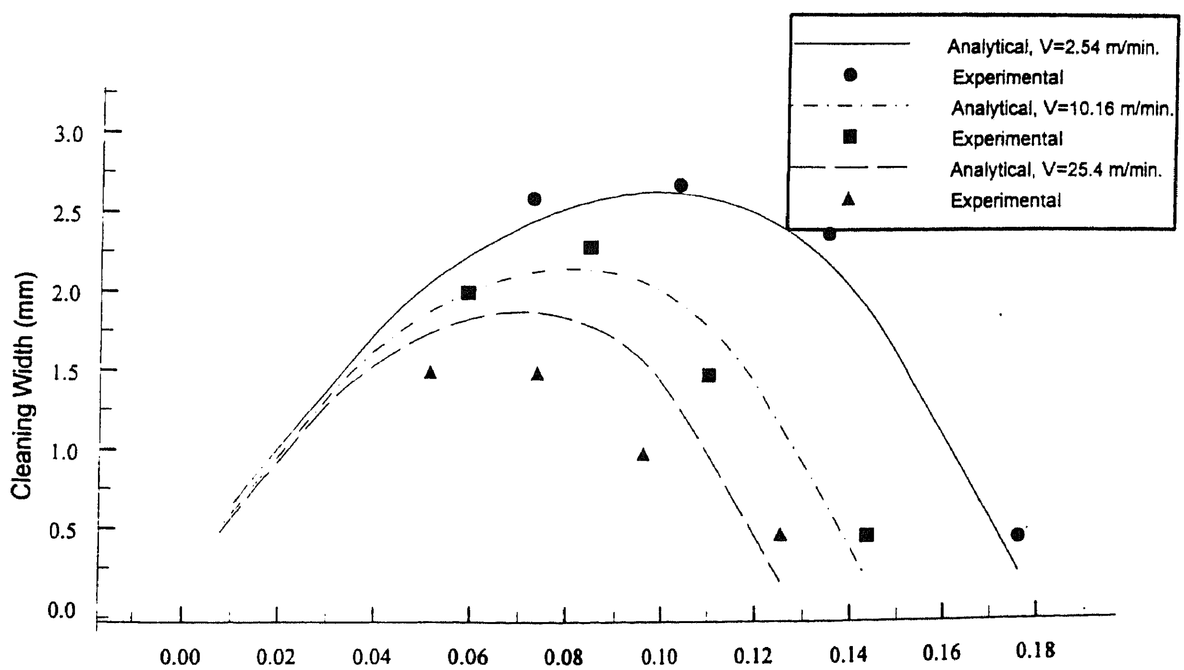

Fig. A.92 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 7 at 138 MPa and three different travel speeds.

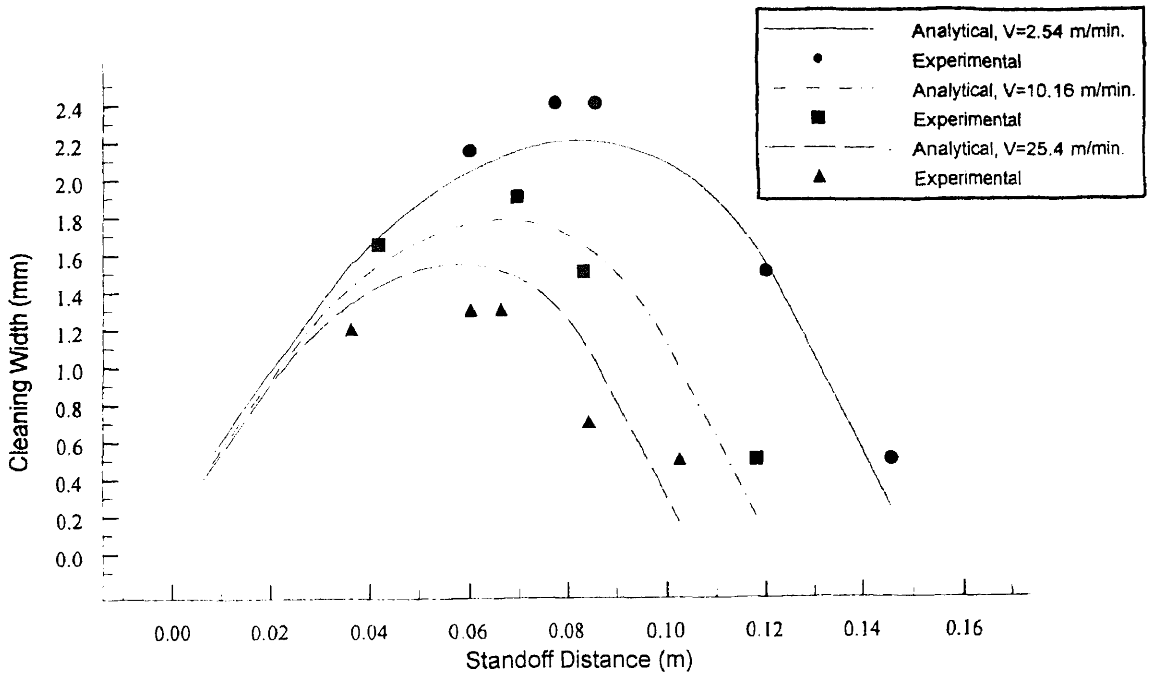

Fig. A.93 Cleaning width vs. standoff distance for moving jet oil-based paint removal with nozzle no. 7 at 69 MPa and three different travel speeds.

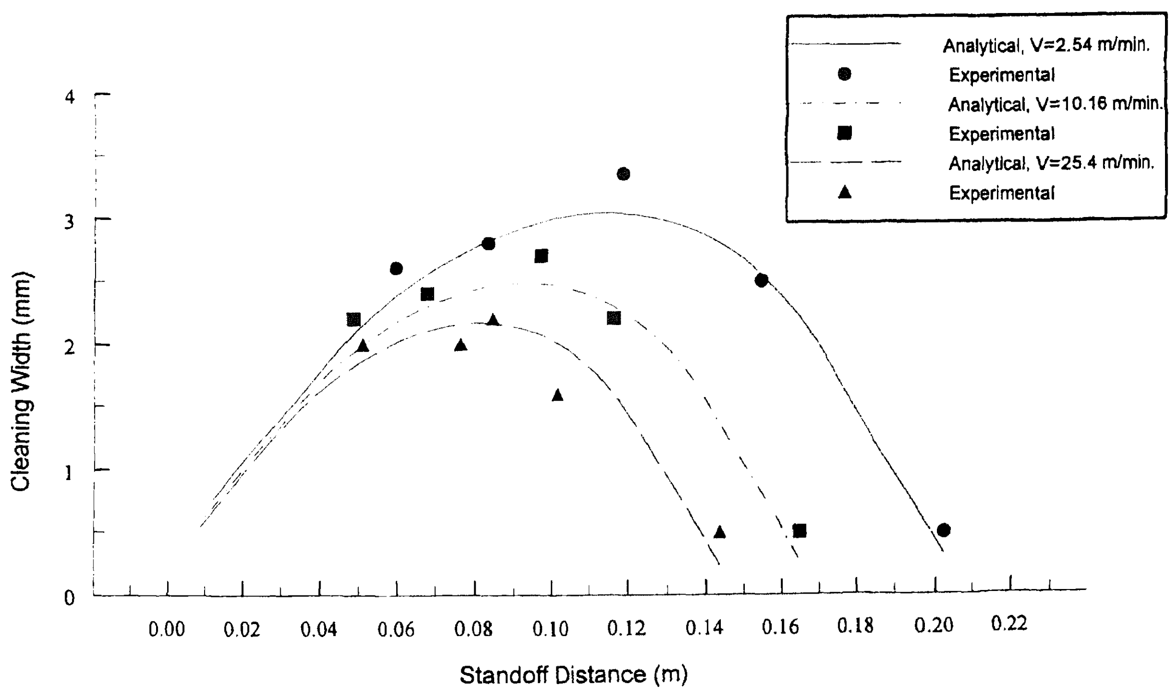

Fig. A.94 Cleaning width vs. standoff distance for moving jet epoxy-based paint removal with nozzle no. 7 at 276 MPa and three different travel speeds.

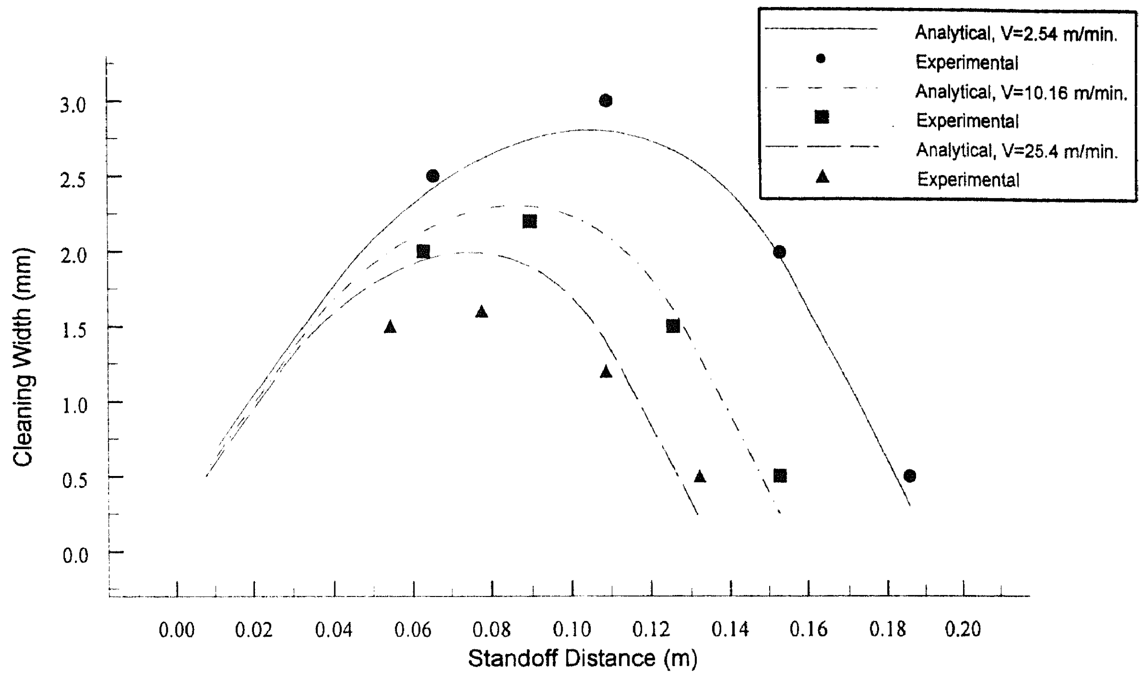

Fig. A.95 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 7 at 207 MPa and three different travel speeds.

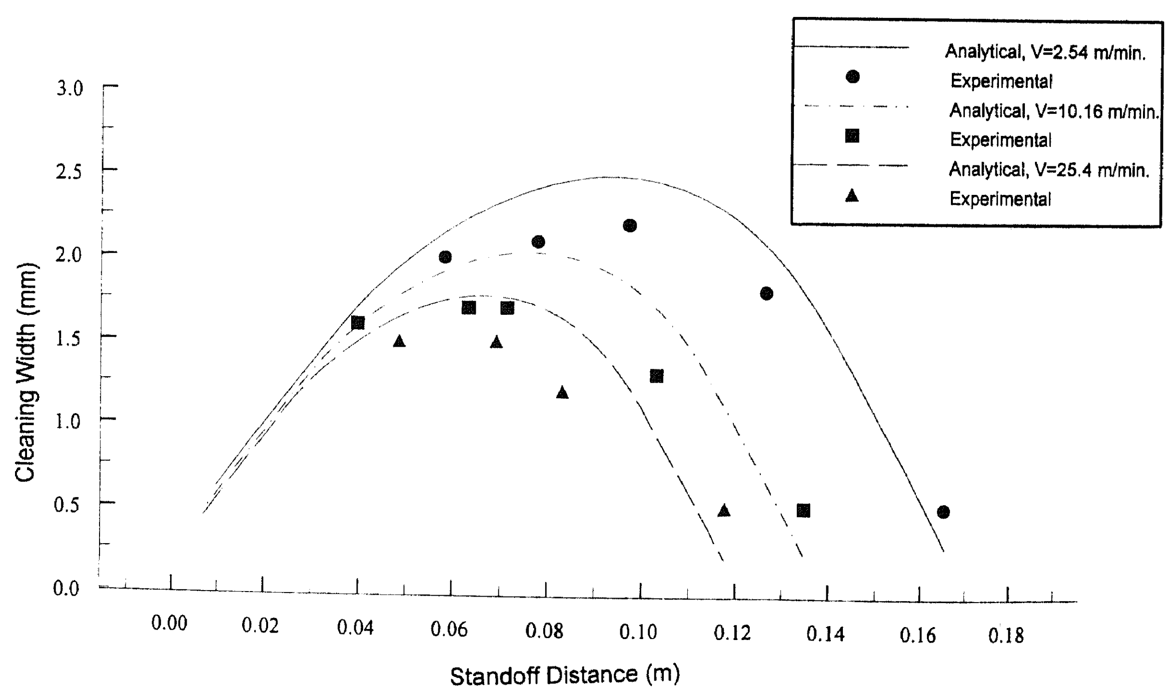

Fig. A.96 Cleaning width vs. standoff distance for moving jet epoxy -based paint removal with nozzle no. 7 at 138 MPa and three different travel speeds.

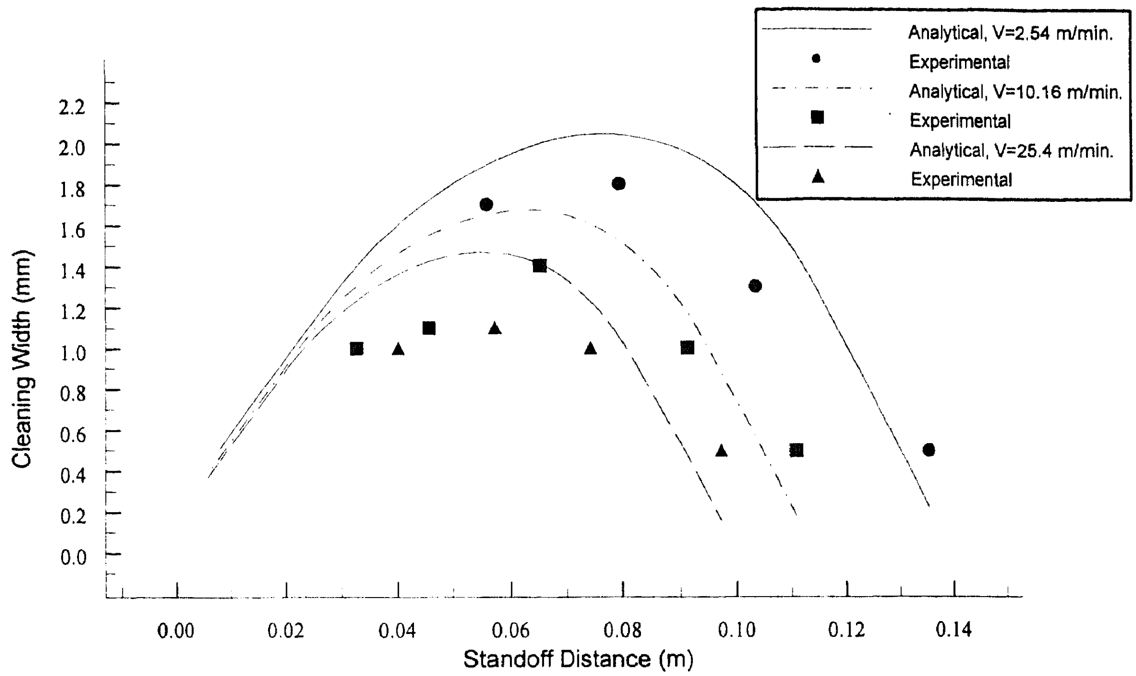

Fig. A.97 Cleaning width vs. standoff distance for moving epoxy oil-based paint removal with nozzle no. 7 at 69 MPa and three different travel speeds.

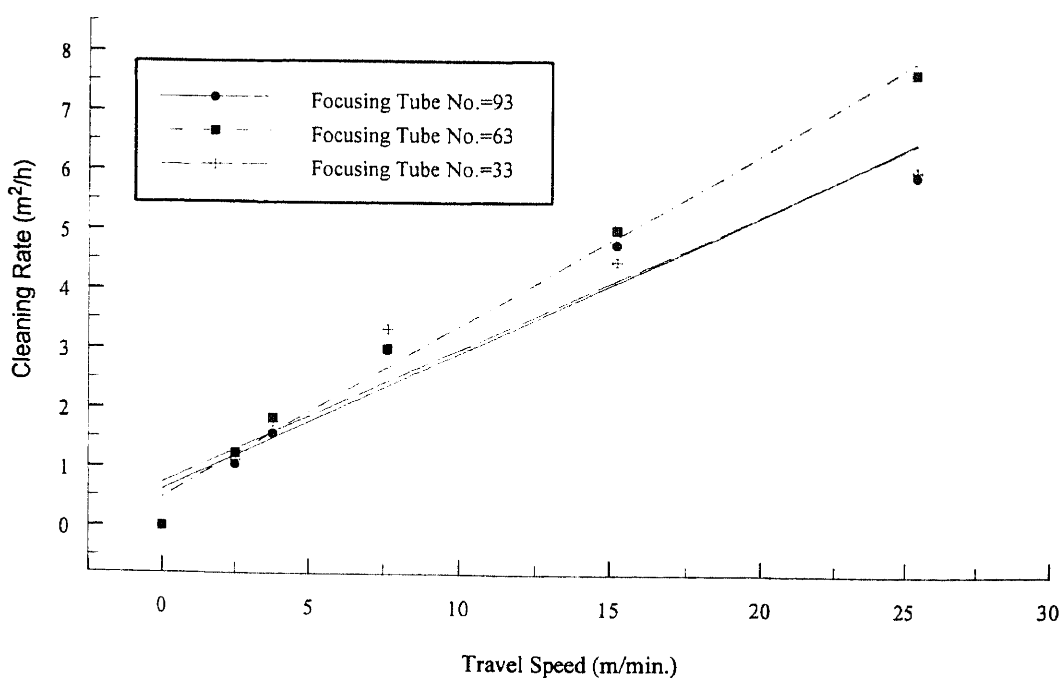

Fig. A.98 Cleaning rate vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 14 and three focusing tubes at 311 MPa.

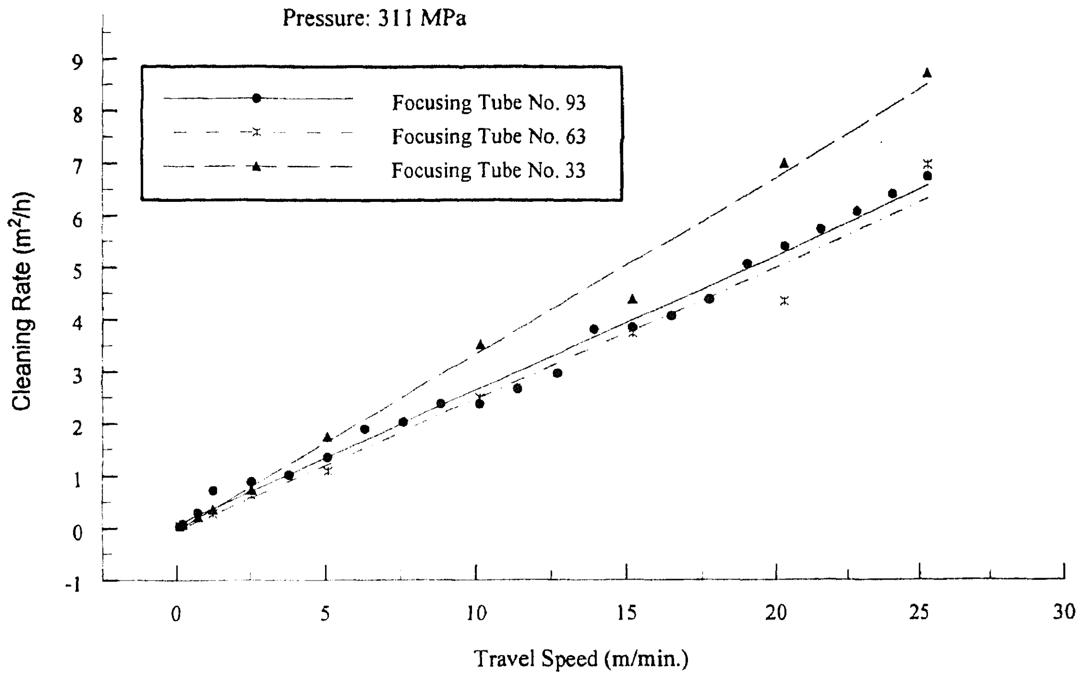

Fig. A.99 Cleaning rate vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 12 and three focusing tubes at 311 MPa.

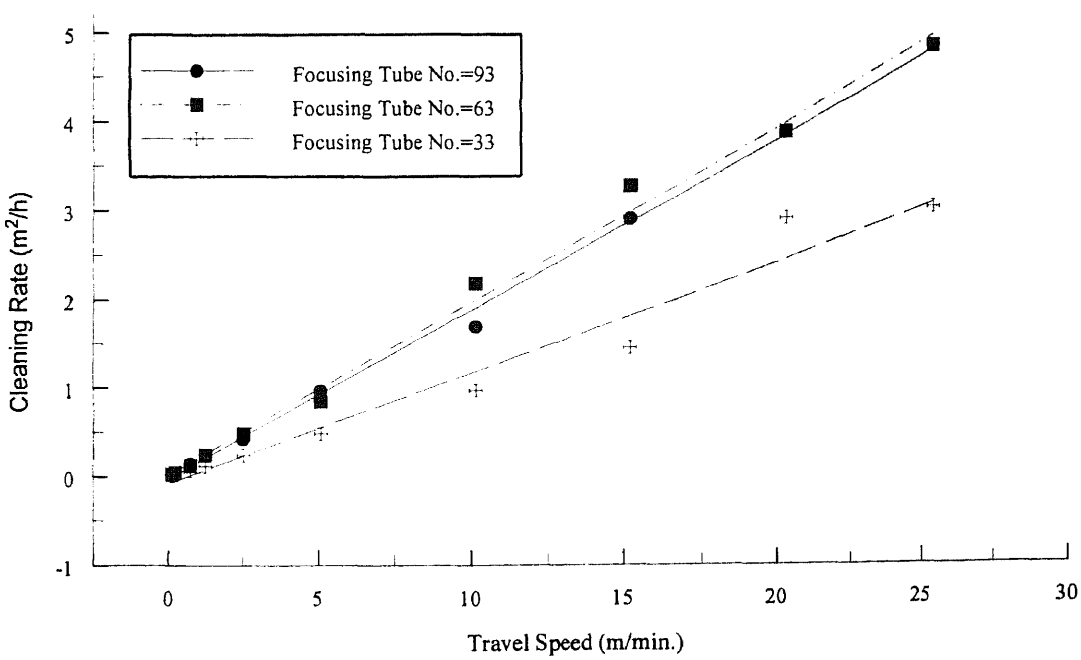

Fig. A.100 Cleaning rate vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 7 and three focusing tubes at 311 MPa.

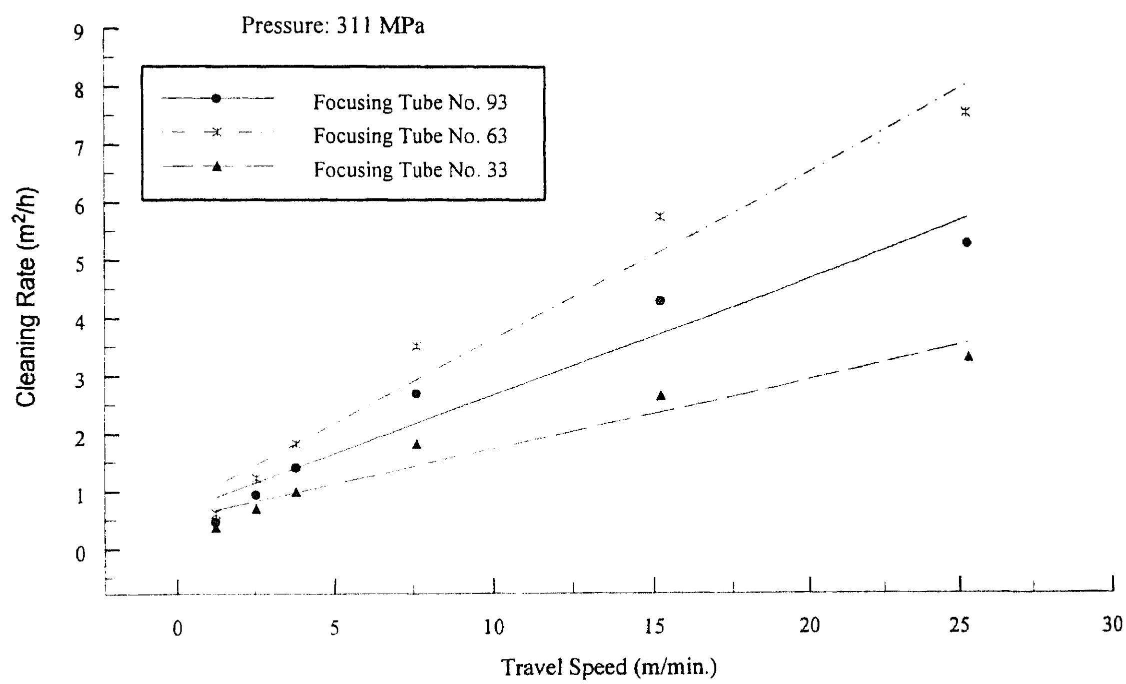

Fig. A.101 Cleaning rate vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 14 and three focusing tubes at 311 MPa.

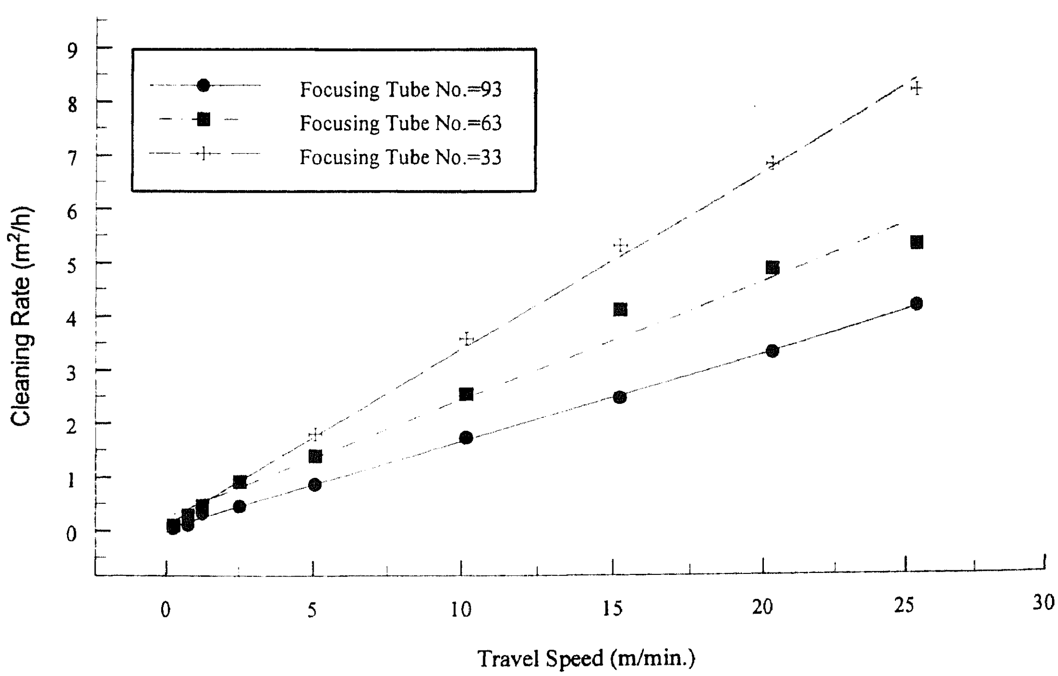

Fig. A.102 Cleaning rate vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 12 and three focusing tubes at 311 MPa.

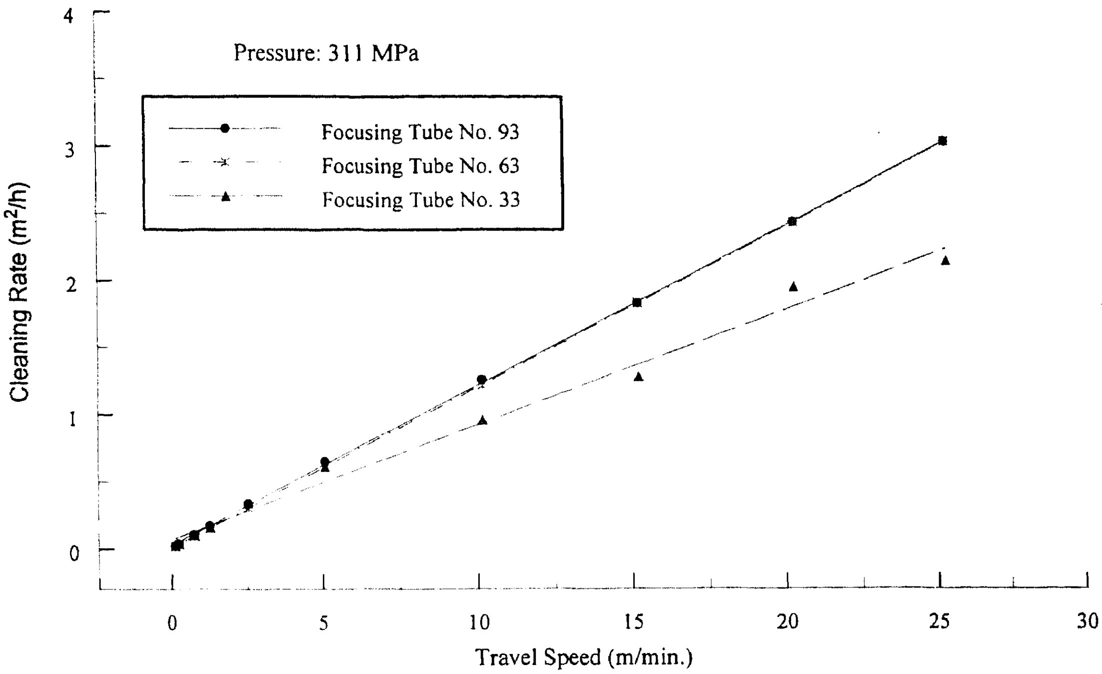

Fig. A.103 Cleaning rate vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 7 and three focusing tubes at 311 MPa.

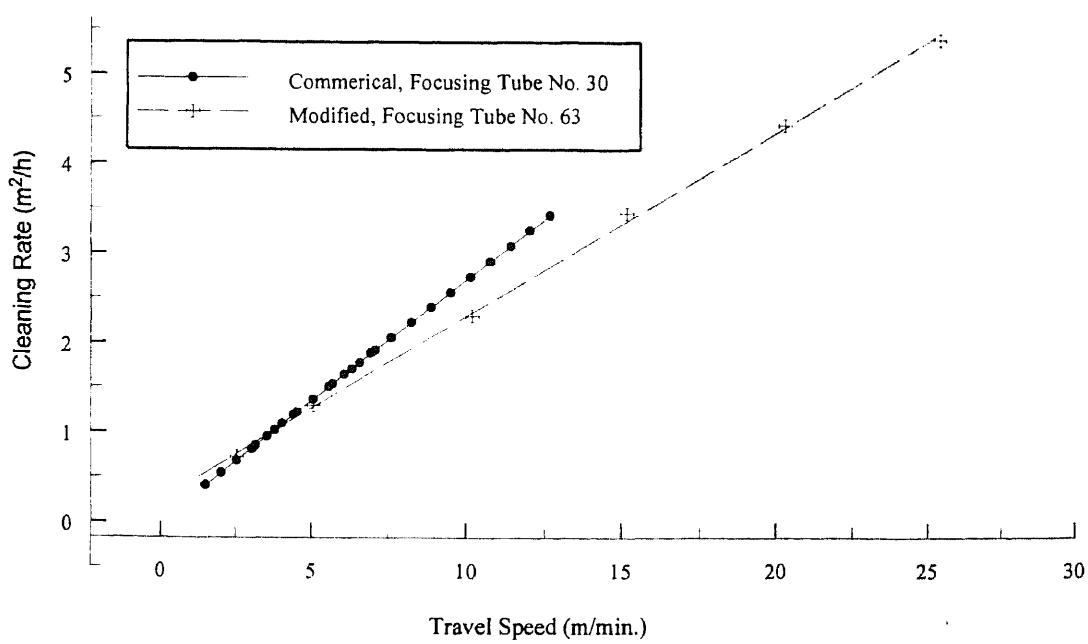

Fig. A.104 Cleaning rate vs. travel speed for oil-based paint removal with the commercial and modified nozzle body, nozzle no. 10 and focusing tubes at 311 MPa.

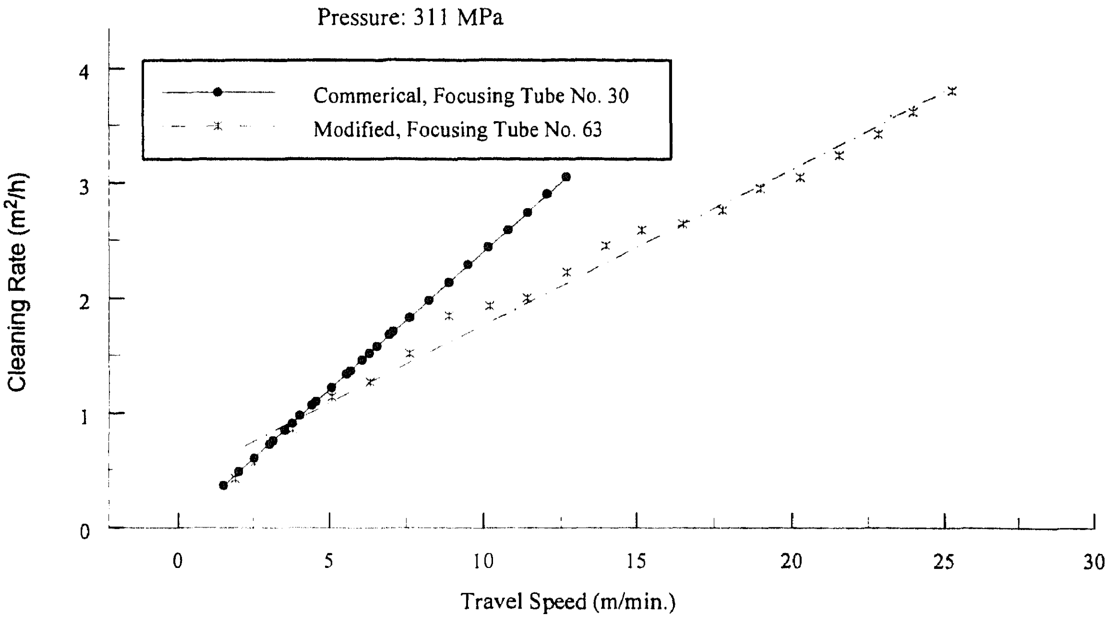

Fig. A.105 Cleaning rate vs. travel speed for epoxy-based paint removal with the commercial and modified nozzle body, nozzle no. 10 and focusing tubes at 311 MPa.

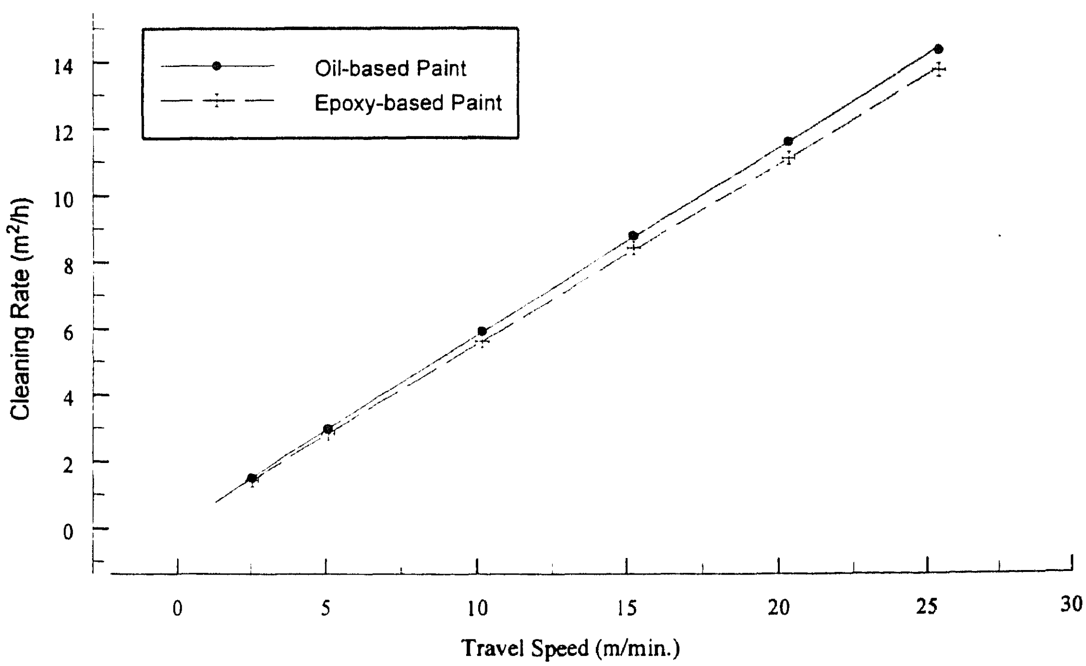

Fig. A.106 Cleaning rate vs. travel speed for oil and epoxy based paint removal with the spiral nozzle body, nozzle no. 12 at 311 MPa.

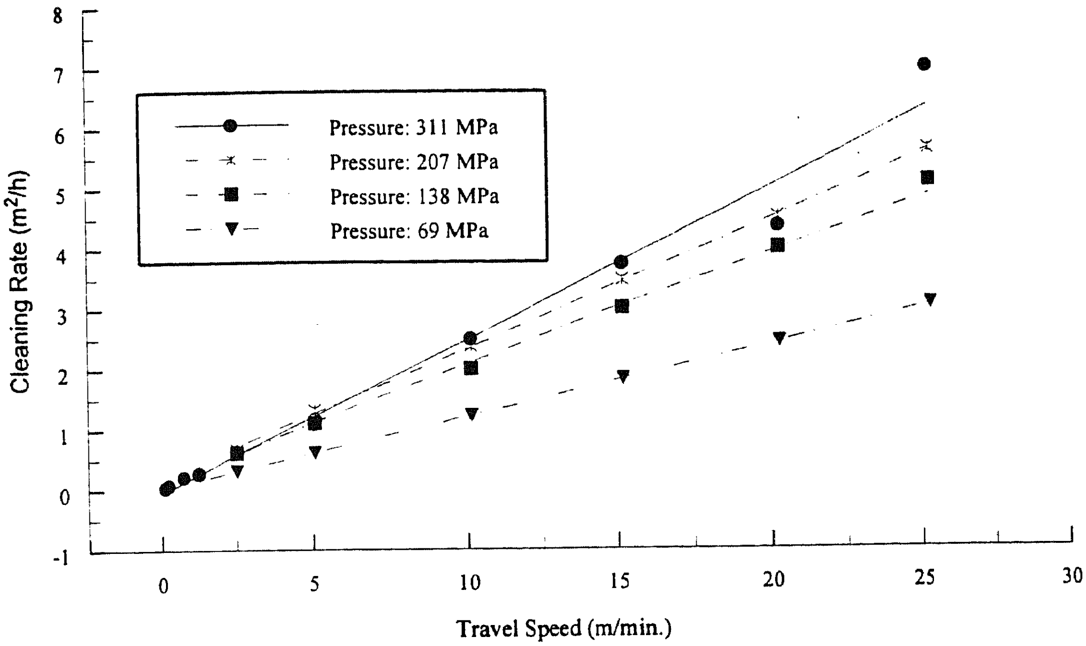

Fig. A.107 Cleaning rate vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 12 and focusing tube no. 63 at different water pressures.

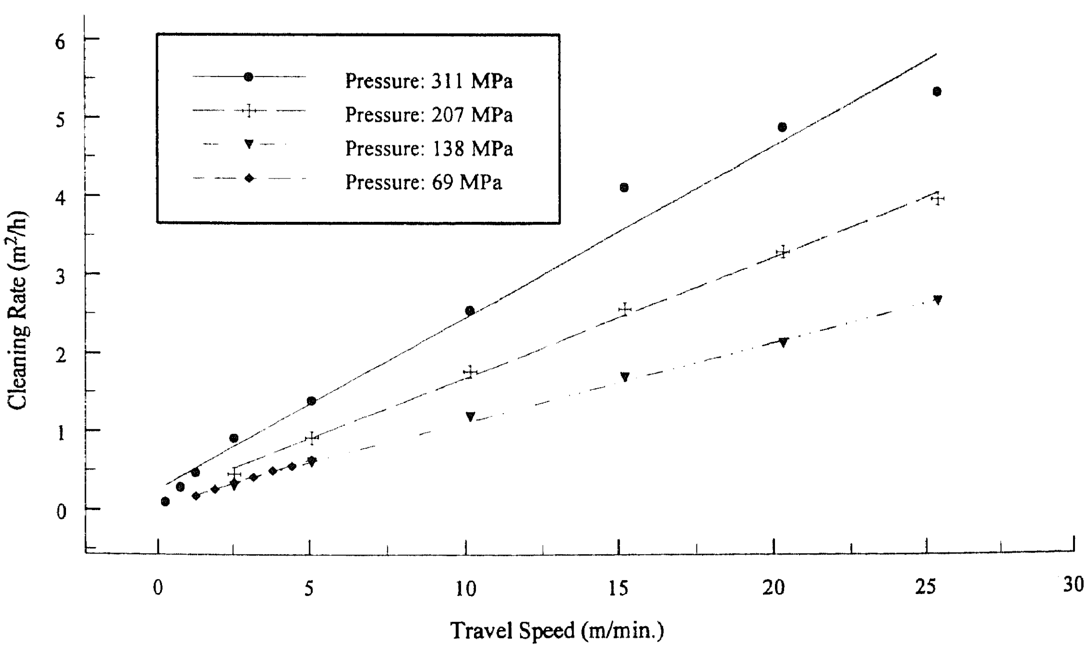

Fig. A.108 Cleaning rate vs. travel speed for epoxy-based paint removal with the modified nozzle body, nozzle no. 12 and focusing tube no. 63 at different water pressures.

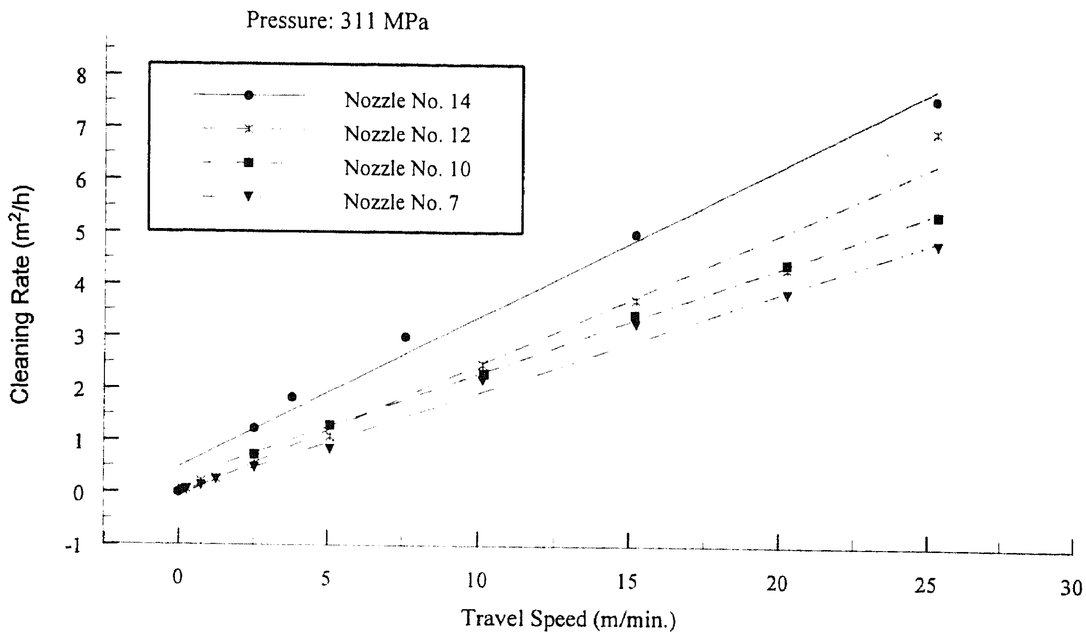

Fig. A.109 Cleaning rate vs. travel speed for oil-based paint removal with the modified nozzle body, different nozzles and focusing tube no. 63 at 311 MPa.

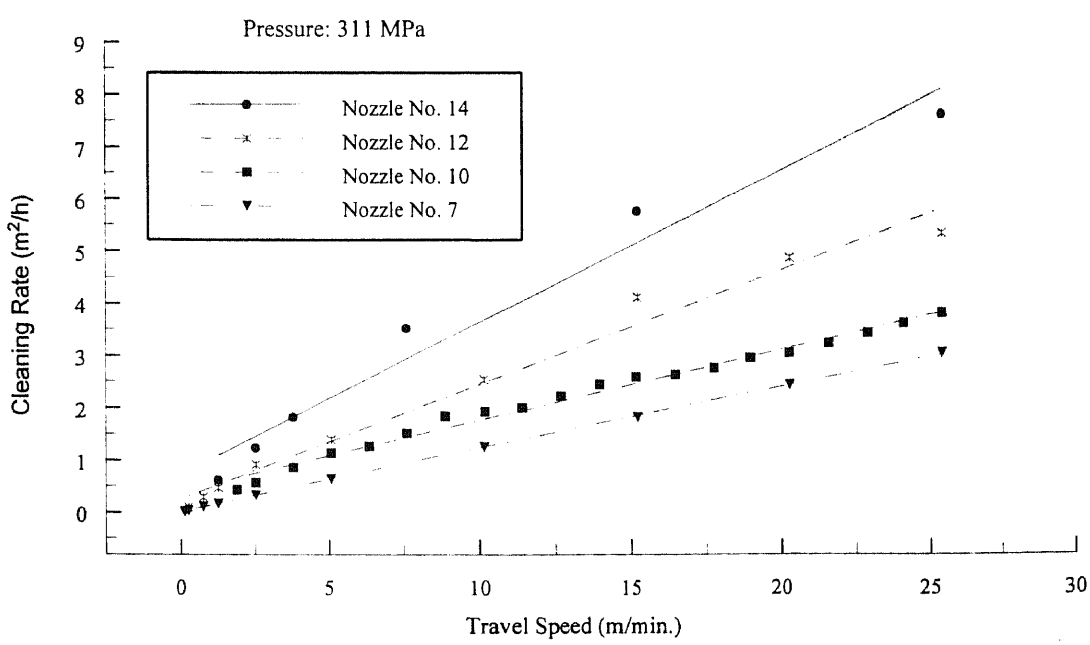

Fig. A.110 Cleaning rate vs. travel speed for epoxy-based paint removal with the modified nozzle body, different nozzles and focusing tube no. 63 at 311 MPa.

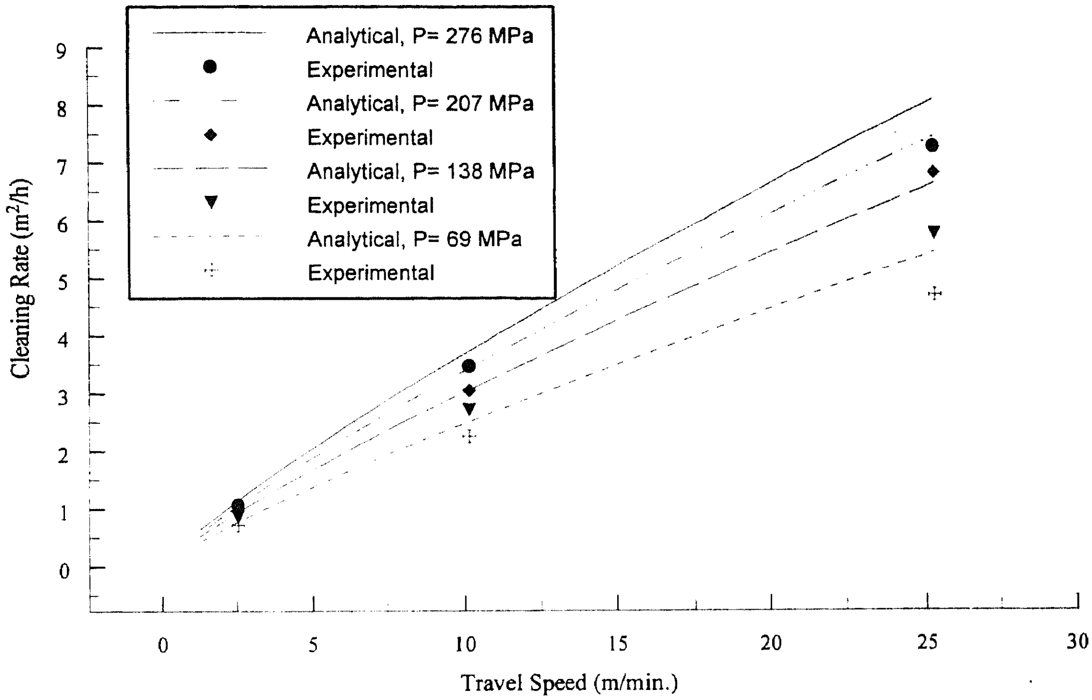

Fig. A.111 Cleaning rate vs. travel speed for oil-based paint removal with sapphire nozzle no. 14 under four different water pressures.

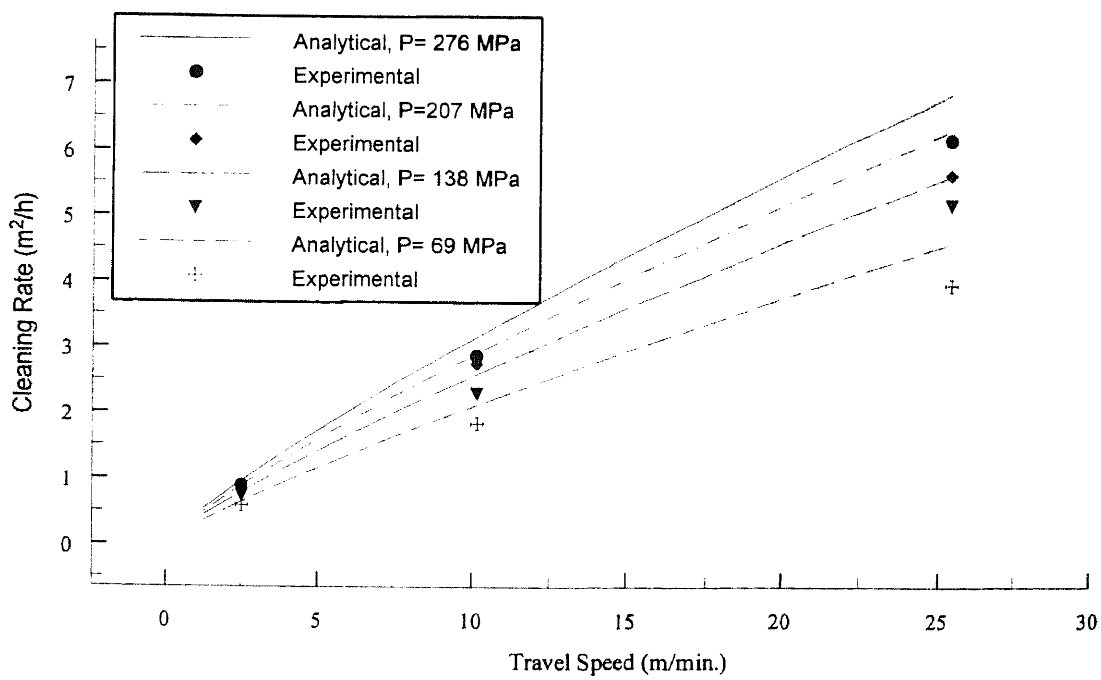

Fig. A.112 Cleaning rate vs. travel speed for oil-based paint removal with sapphire nozzle no. 12 under four different water pressures.

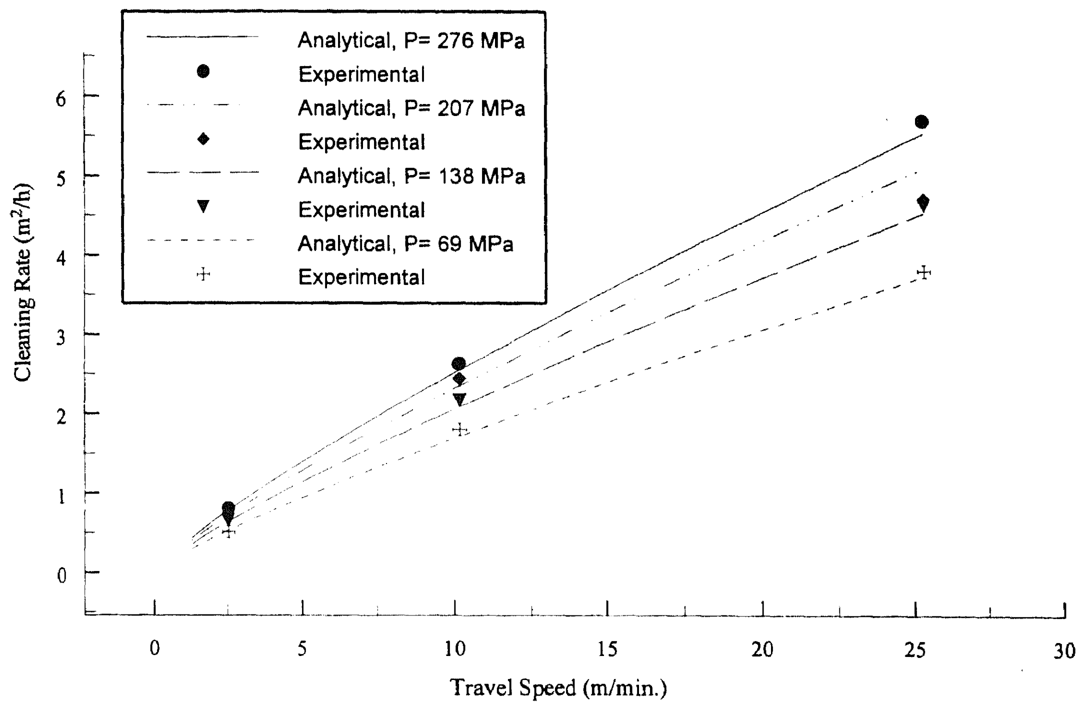

Fig. A.113 Cleaning rate vs. travel speed for oil-based paint removal with sapphire nozzle no. 10 under four different water pressures.

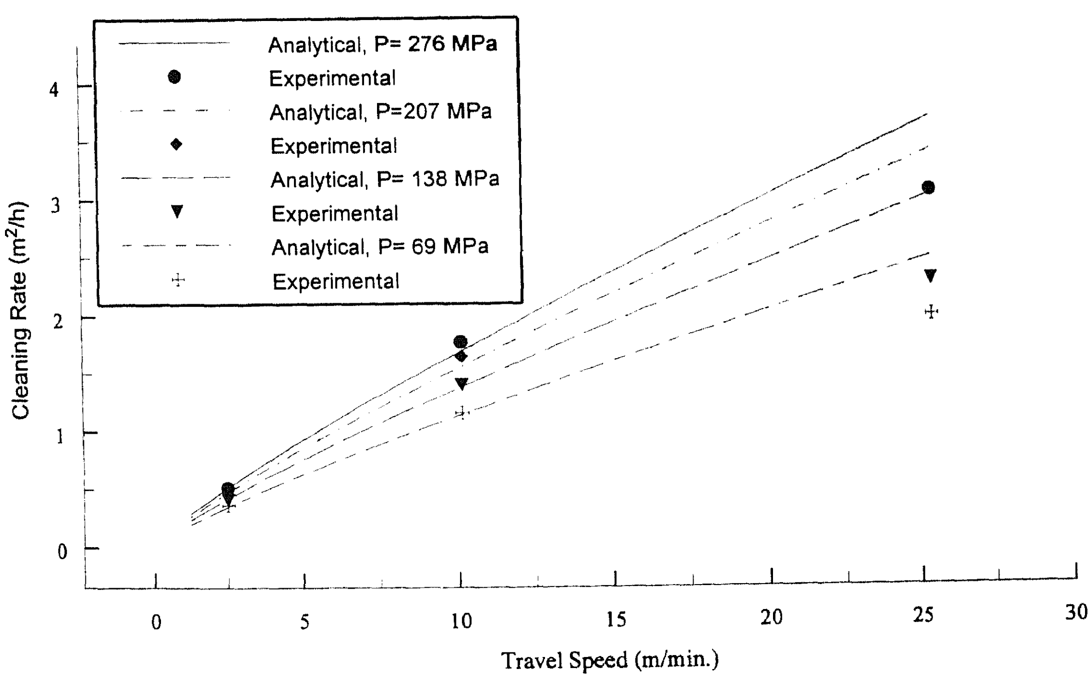

Fig. A.114 Cleaning rate vs. travel speed for oil-based paint removal with sapphire nozzle no. 7 under four different water pressures.

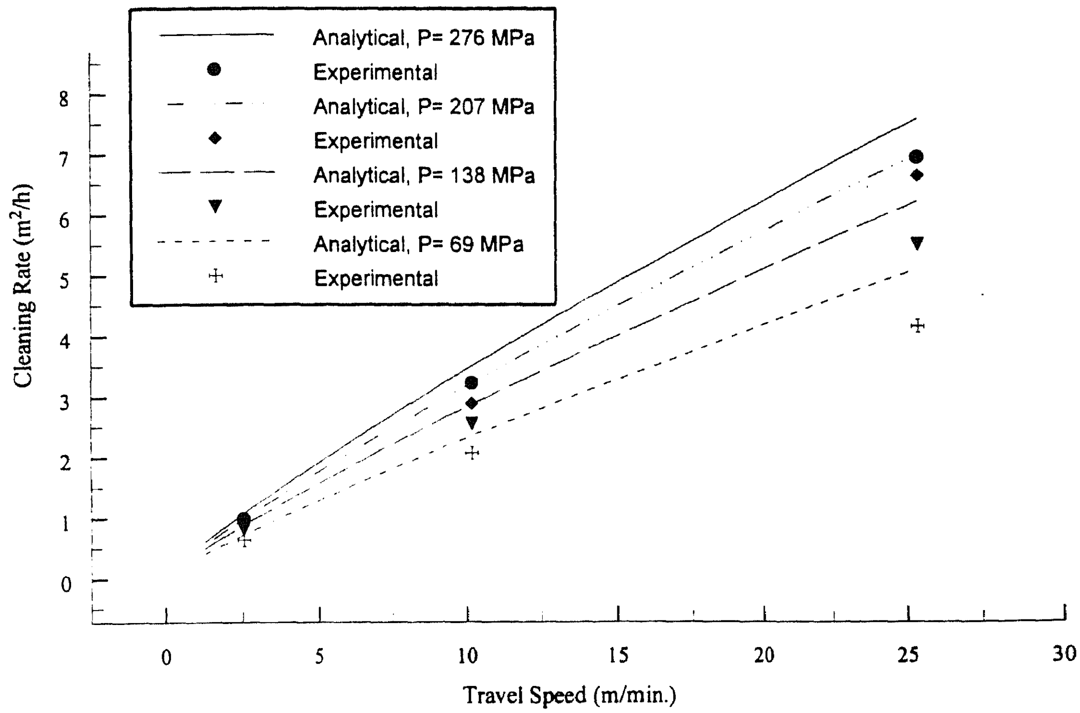

Fig. A.115 Cleaning rate vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 14 under four different water pressures.

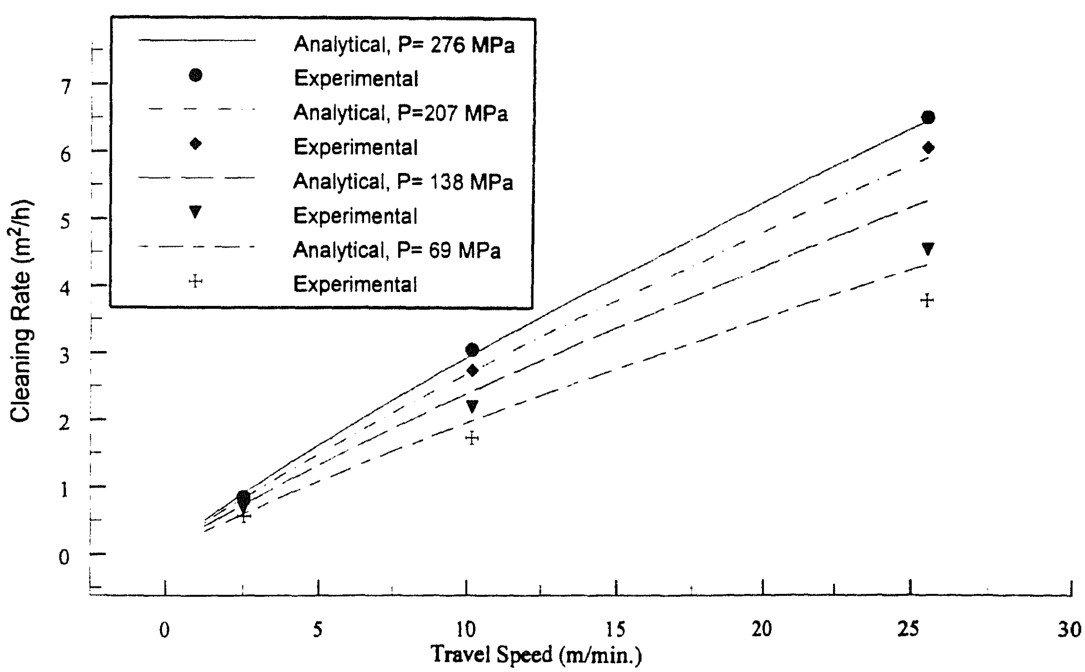

Fig. A.116 Cleaning rate vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 12 under four different water pressures.

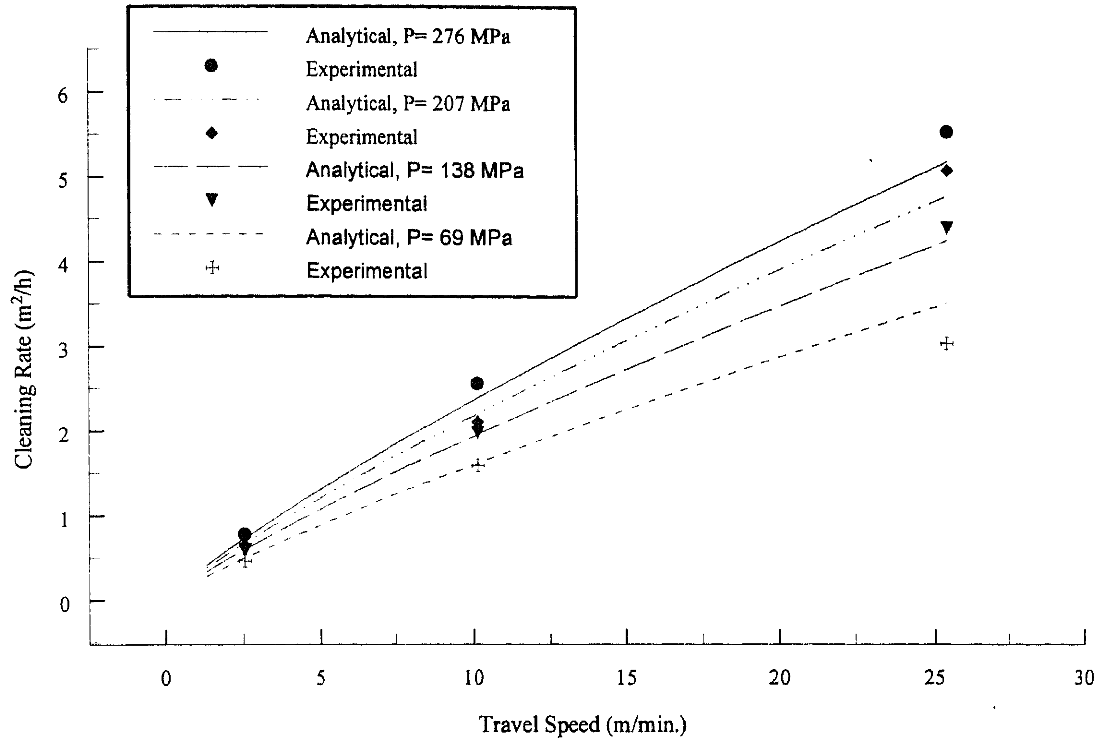

Fig. A.117 Cleaning rate vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 10 under four different water pressures.

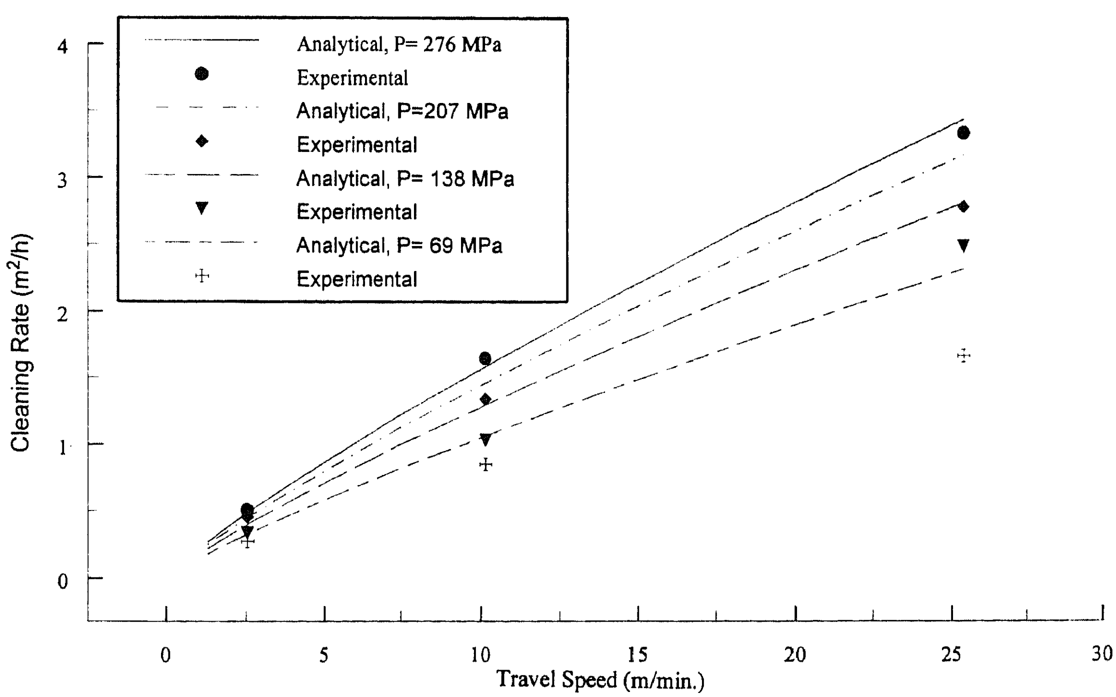

Fig. A.118 Cleaning rate vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 7 under four different water pressures.

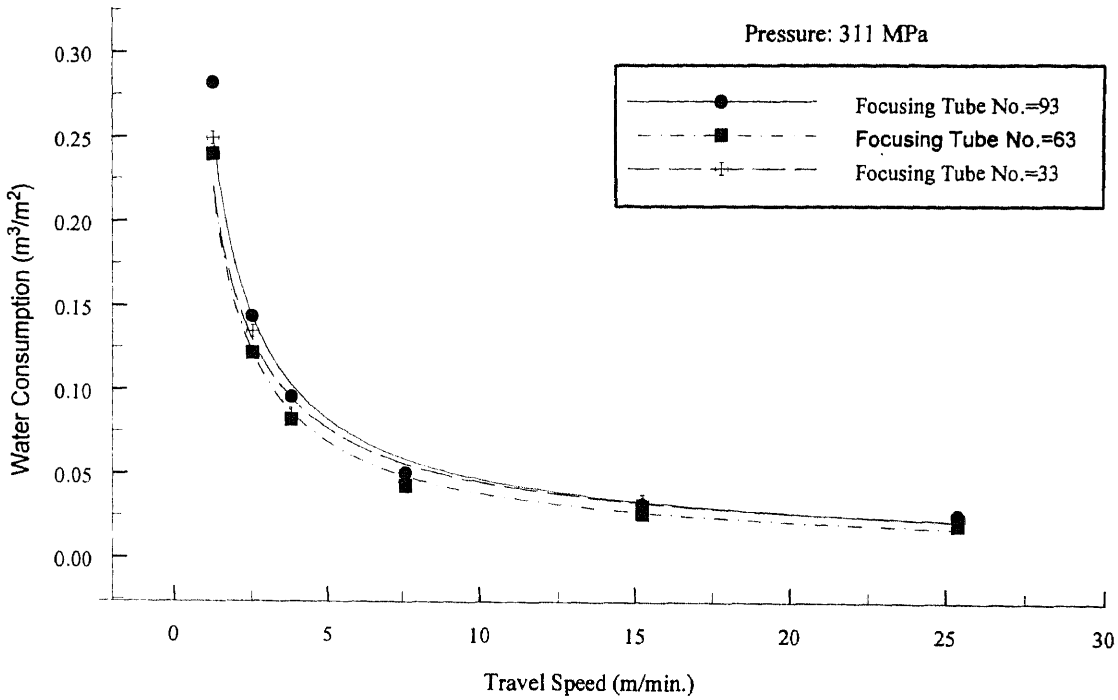

Fig. A.119 Water consumption vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 14 and three focusing tubes at 311 MPa.

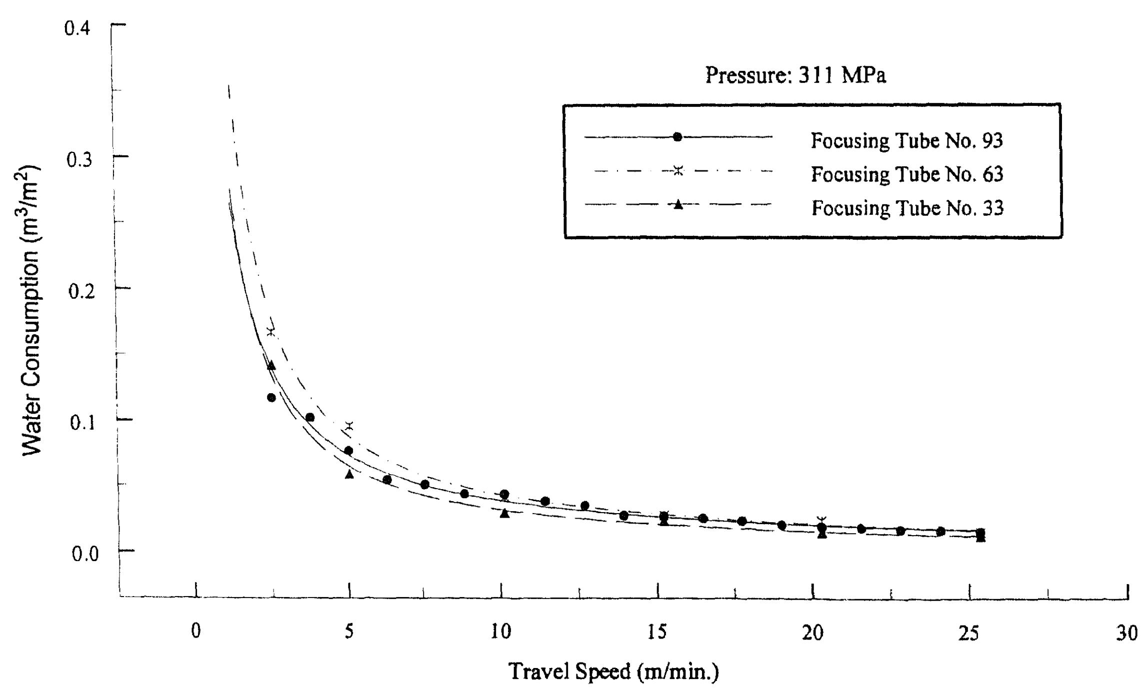

Fig. A.120 Water consumption vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 12 and three focusing tubes at 311 MPa.

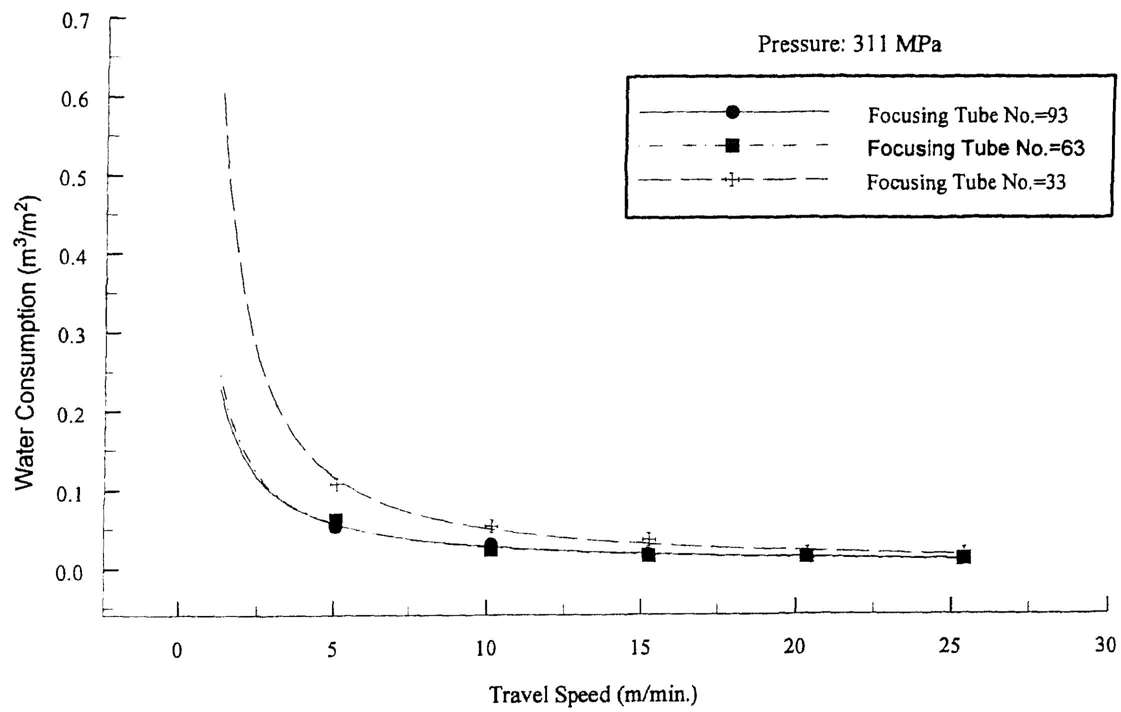

Fig. A.121 Water consumption vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 7 and three focusing tubes at 311 MPa.

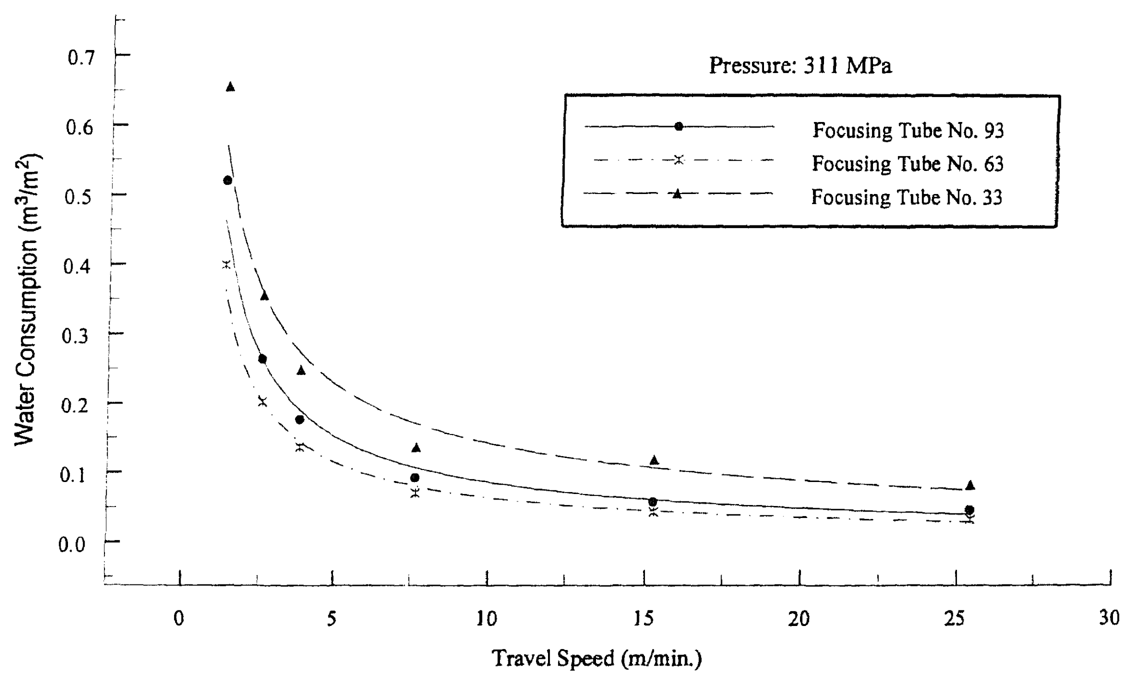

Fig. A.122 Water consumption vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 14 and three focusing tubes at 311 MPa.

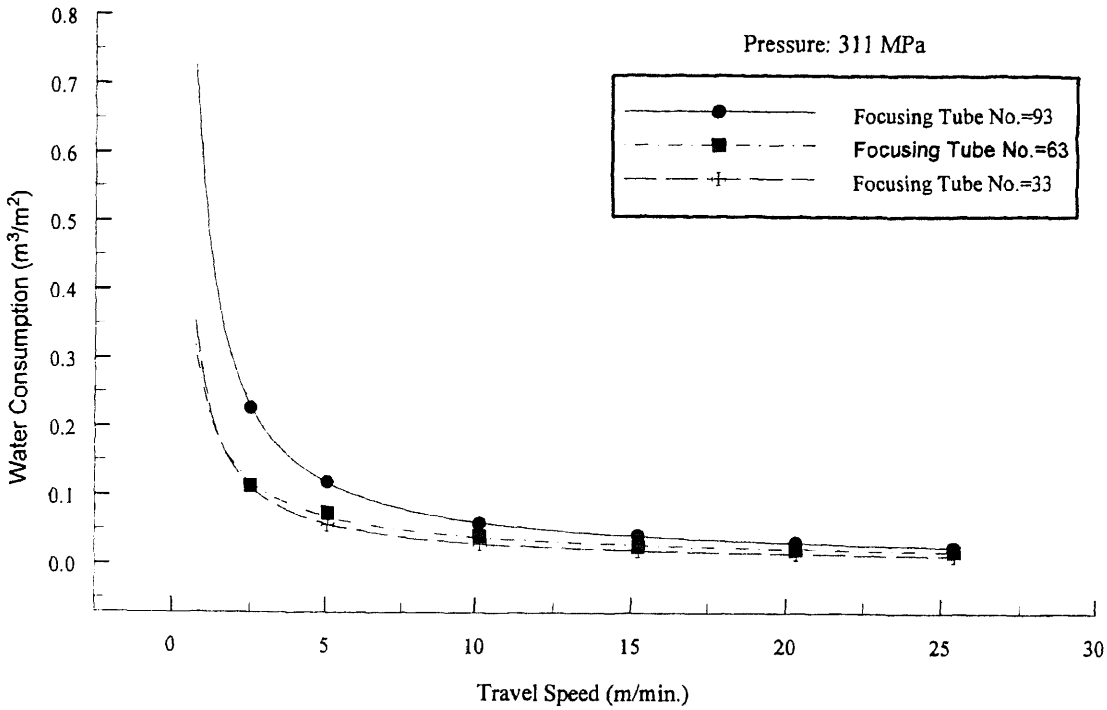

Fig. A.123 Water consumption vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 12 and three focusing tubes at 311 MPa.

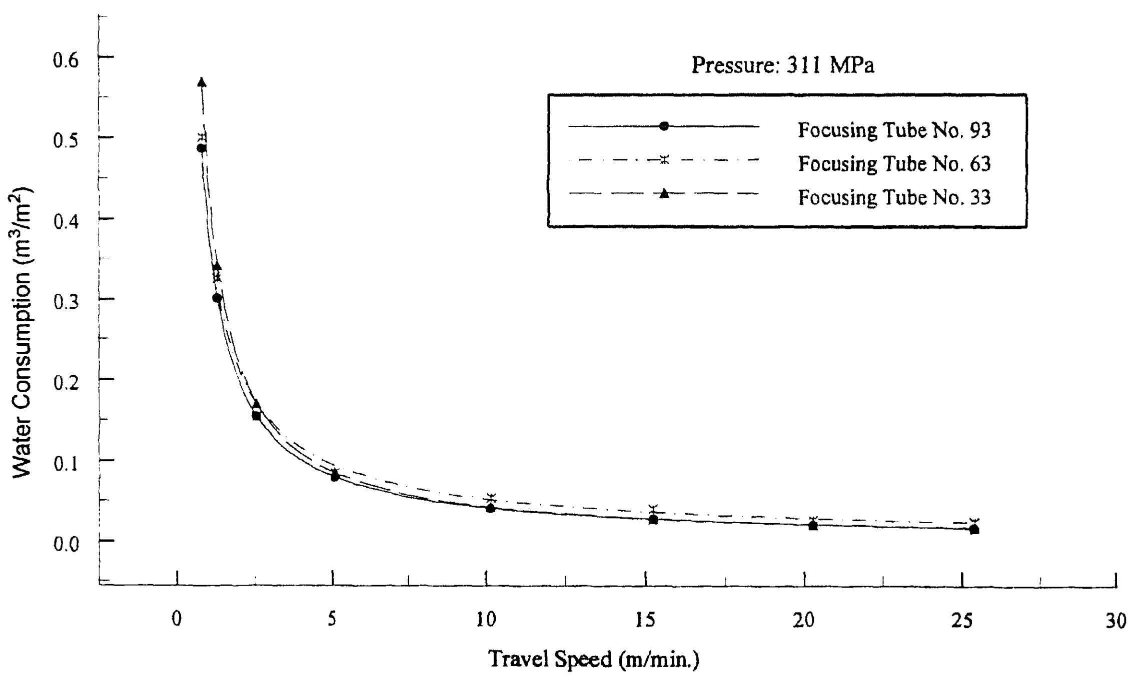

Fig. A.124 Water consumption vs. travel speed for epoxy-based paint removal with modified nozzle body, nozzle no. 7 and three focusing tubes at 311 MPa.

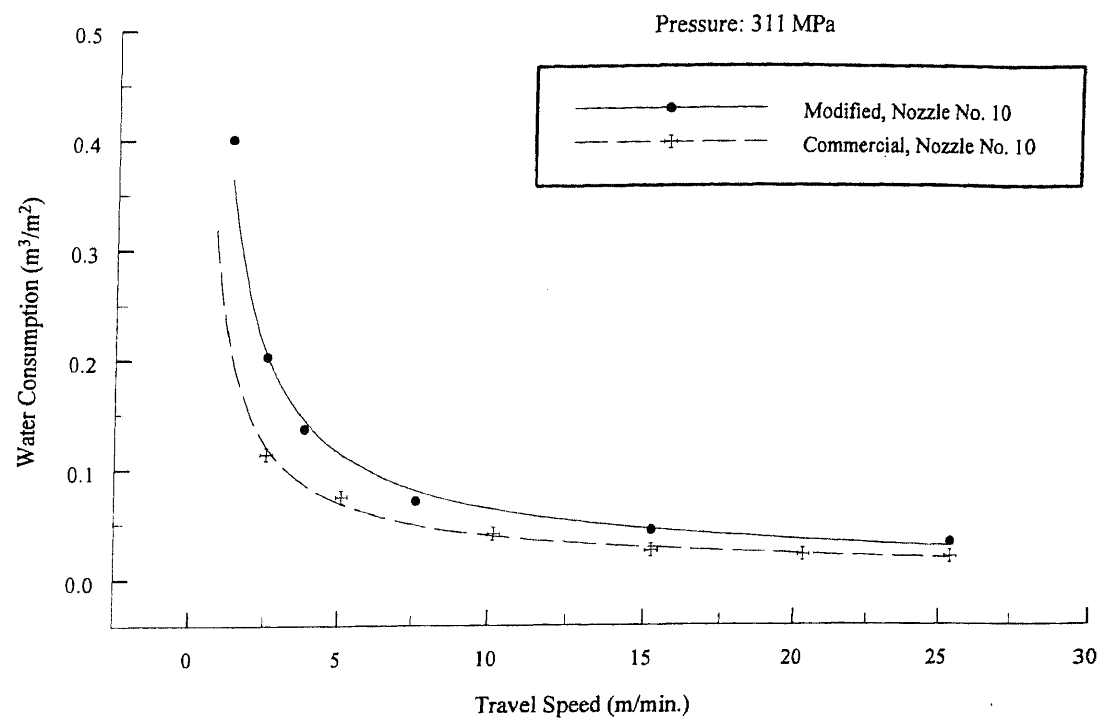

Fig. A.125 Water consumption vs. travel speed for oil-based paint removal with the commercial and modified nozzle body, nozzle no. 10 and focusing tubes at 311 MPa.

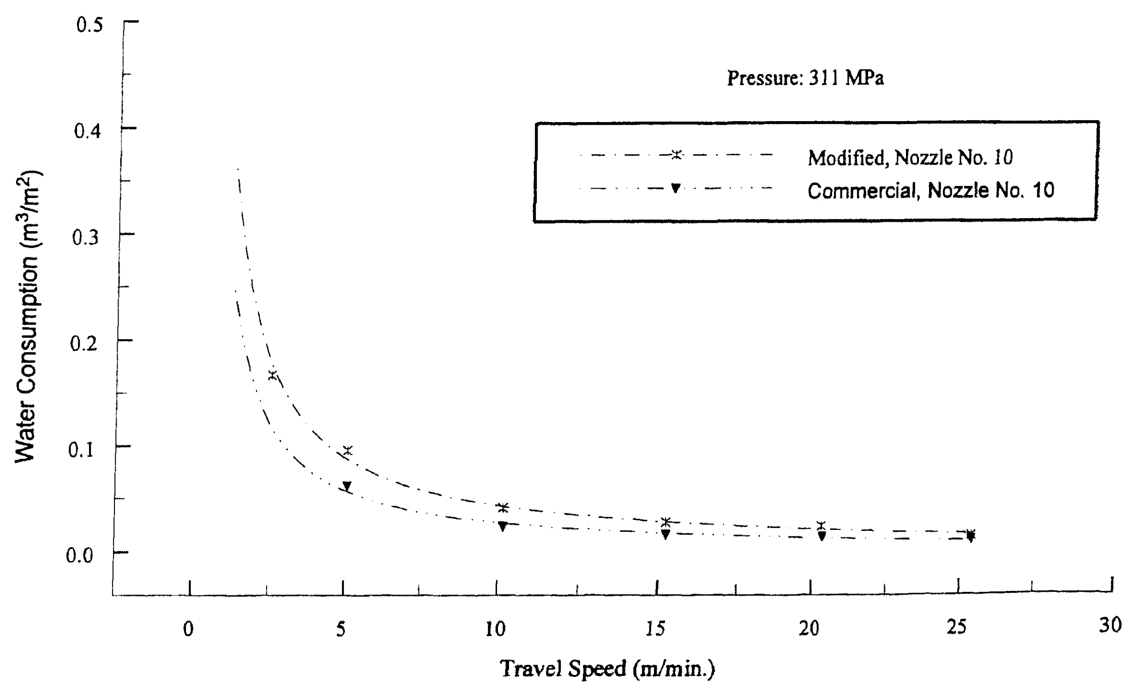

Fig. A.126 Water consumption vs. travel speed for epoxy-based paint removal with the commercial and modified nozzle body, nozzle no. 10 and focusing tubes at 311 MPa.

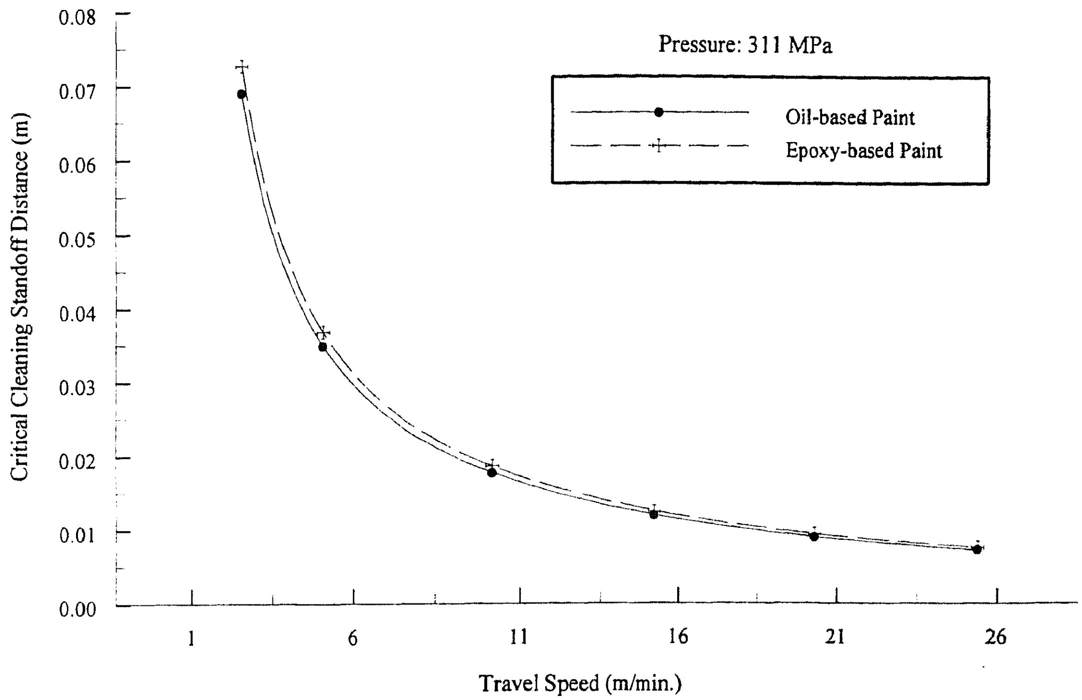

Fig. A.127 Water consumption vs. travel speed for oil and epoxy based paint removal with the spiral nozzle body, nozzle no. 12 at 311 MPa.

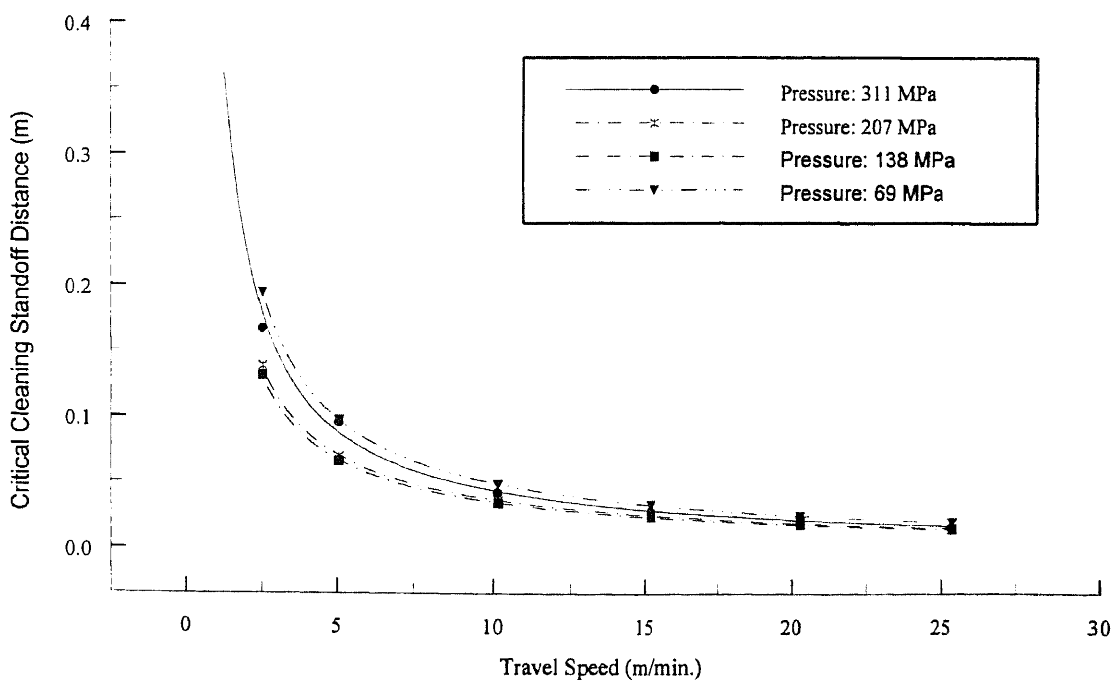

Fig. A.128 Water consumption vs. travel speed for oil-based paint removal with the modified nozzle body, nozzle no. 12 and focusing tube no. 63 at different water pressures.

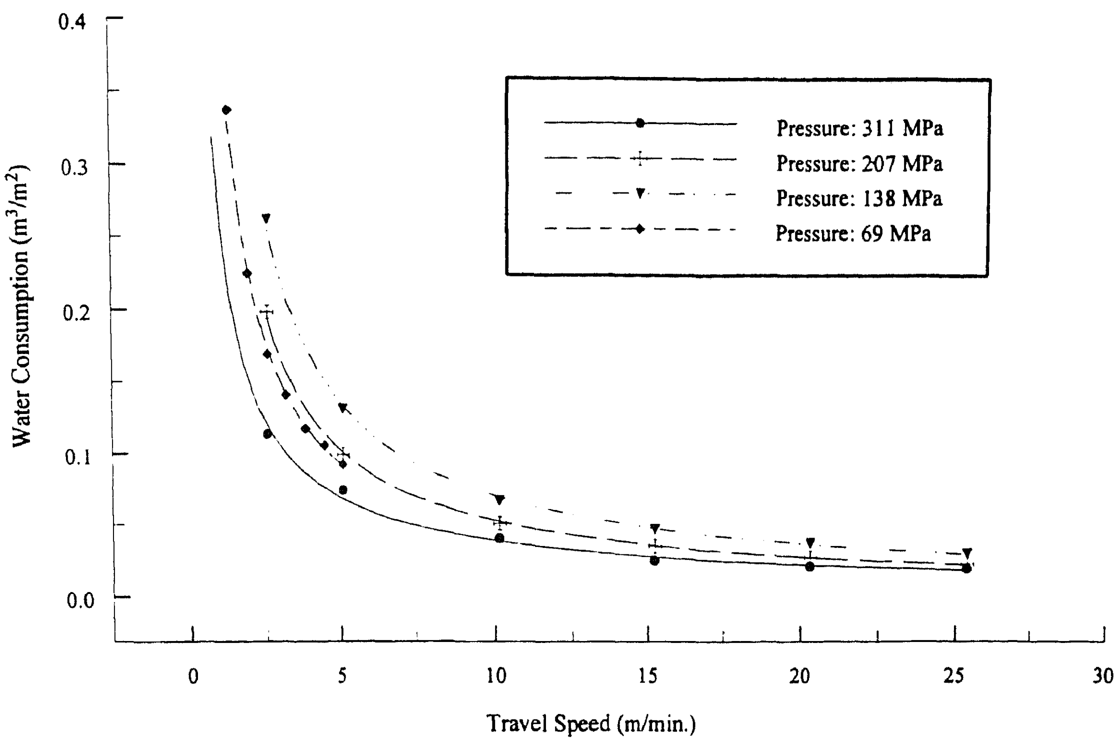

Fig. A.129 Water consumption vs. travel speed for epoxy-based paint removal with the modified nozzle body, nozzle no. 12 and focusing tube no. 63 at different water pressures.

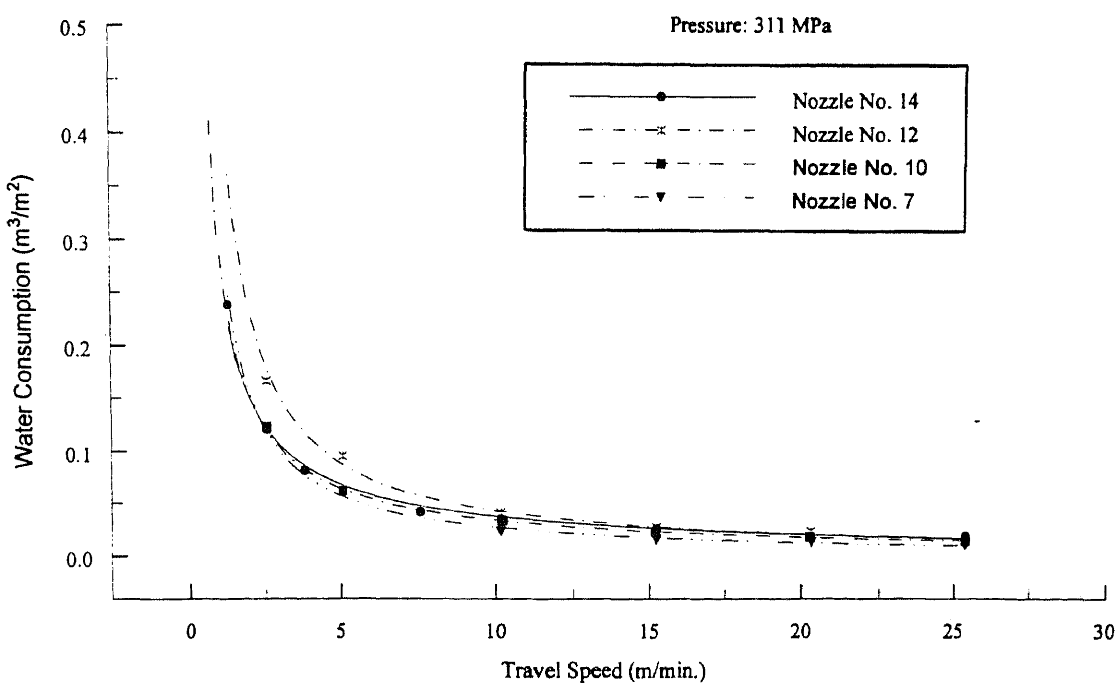

Fig. A.130 Water consumption vs. travel speed for oil-based paint removal with the modified nozzle body, different nozzles and focusing tube no. 63 at 311 MPa.

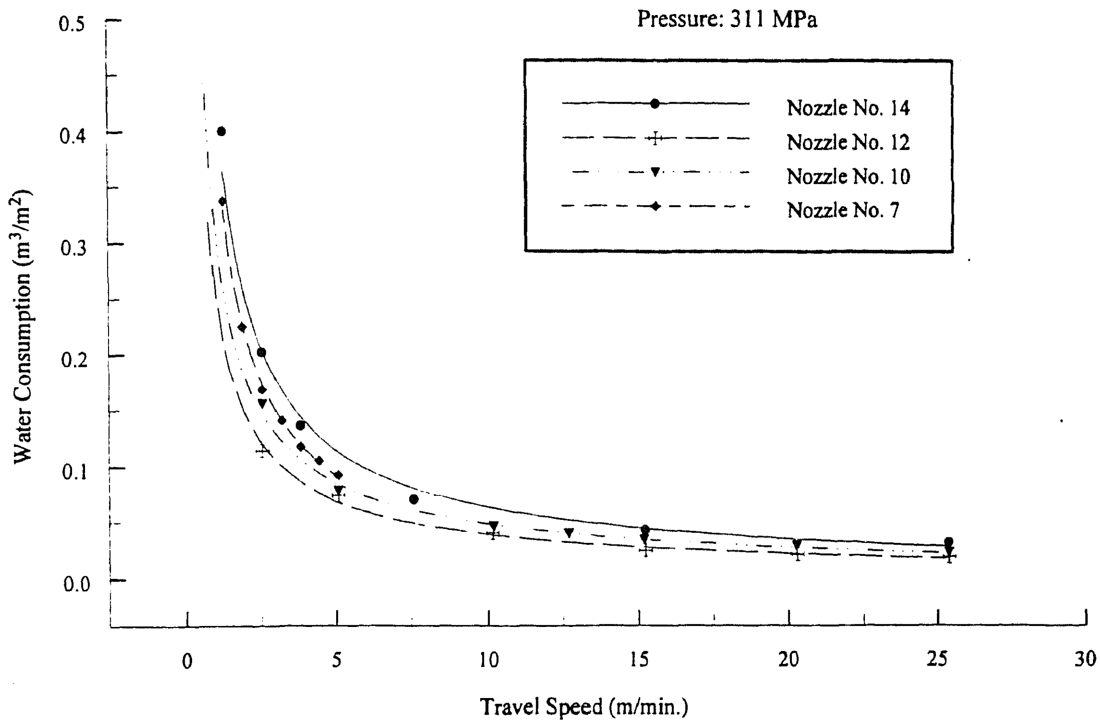

Fig. A.131 Water consumption vs. travel speed for epoxy-based paint removal with the modified nozzle body, different nozzles and focusing tube no. 63 at 311 MPa.

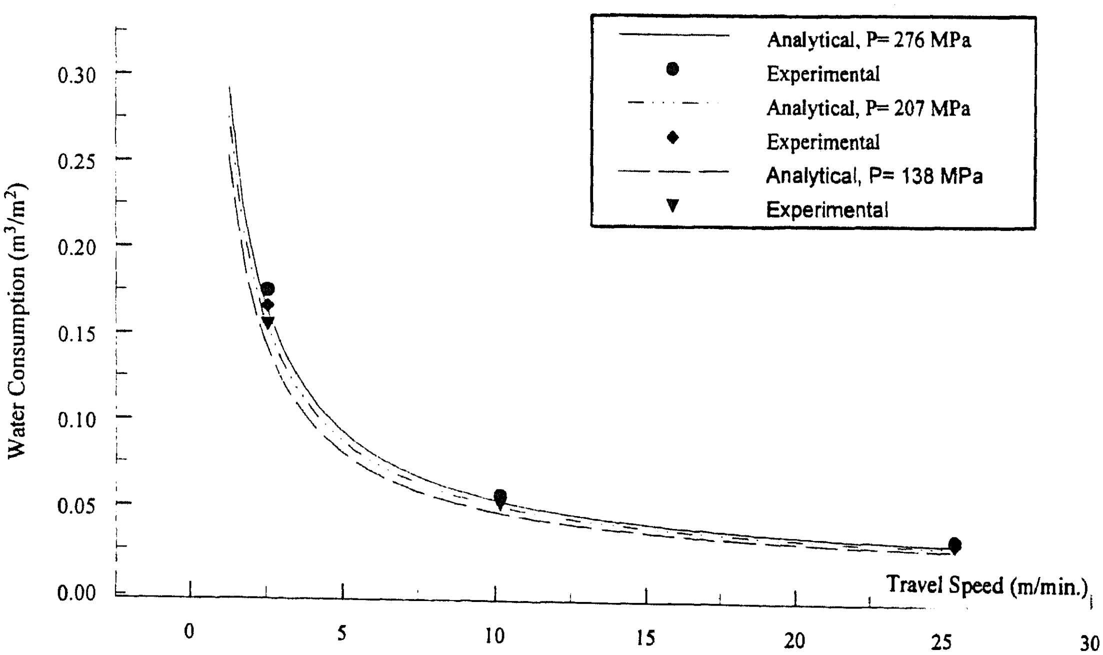

Fig. A.132 Water consumption vs. travel speed for oil-based paint removal with sapphire nozzle no. 14 under four different water pressures.

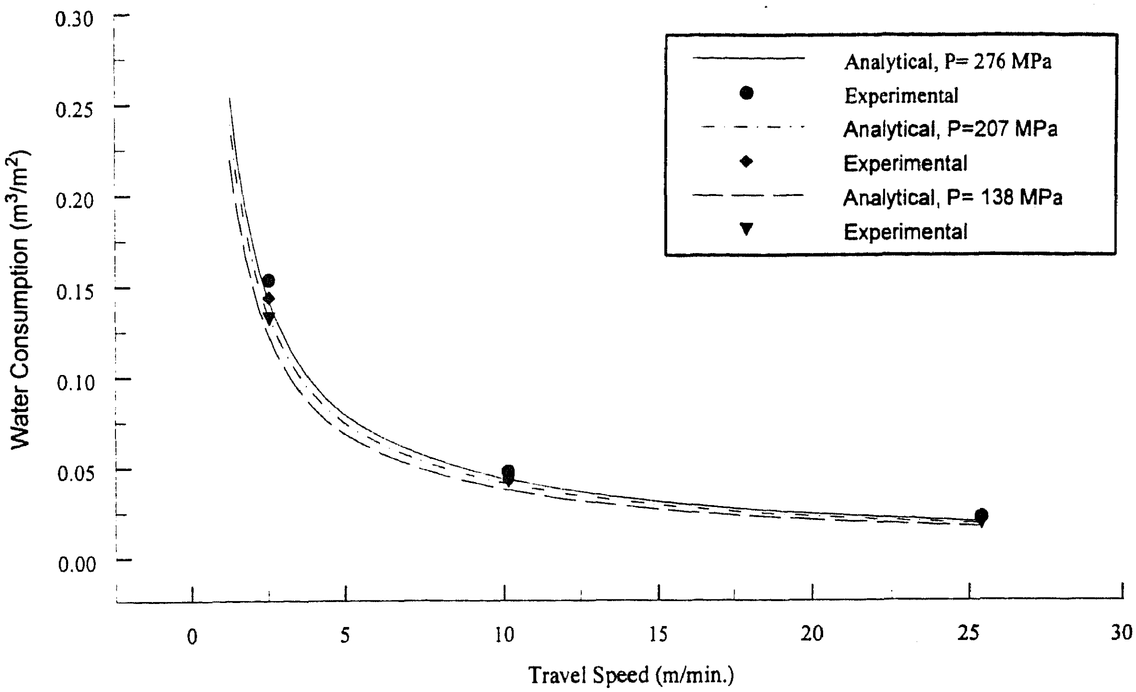

Fig. A.133 Water consumption vs. travel speed for oil-based paint removal with sapphire nozzle no. 12 under four different water pressures.

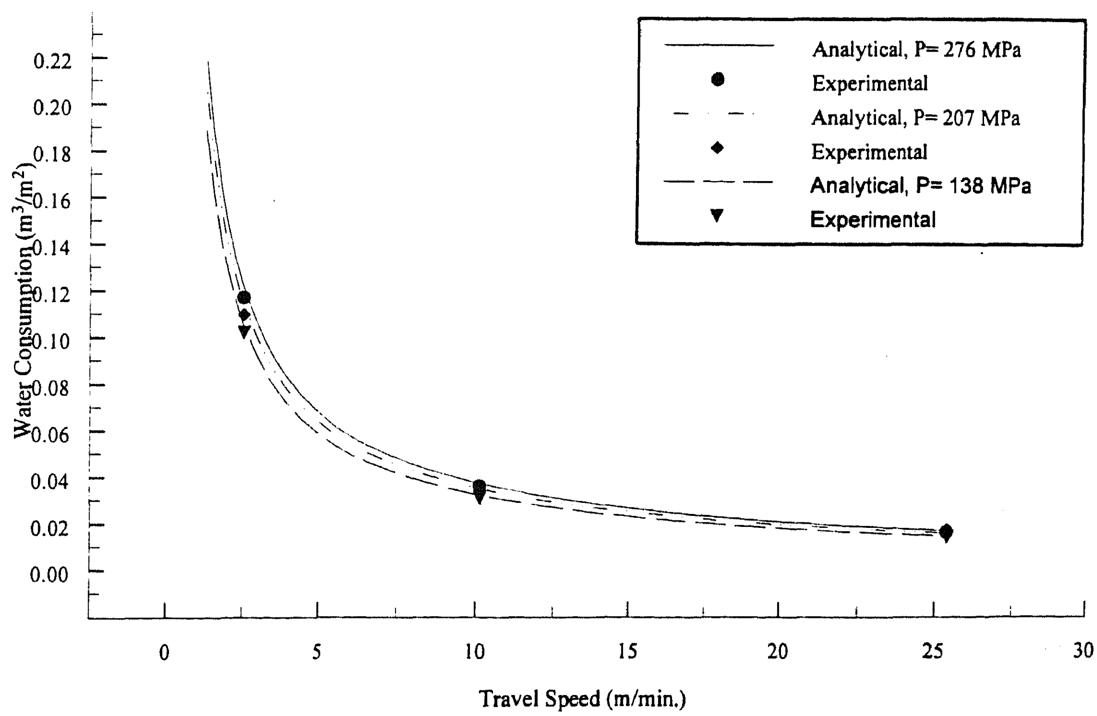

Fig. A.134 Water consumption vs. travel speed for oil-based paint removal with sapphire nozzle no. 10 under four different water pressures.

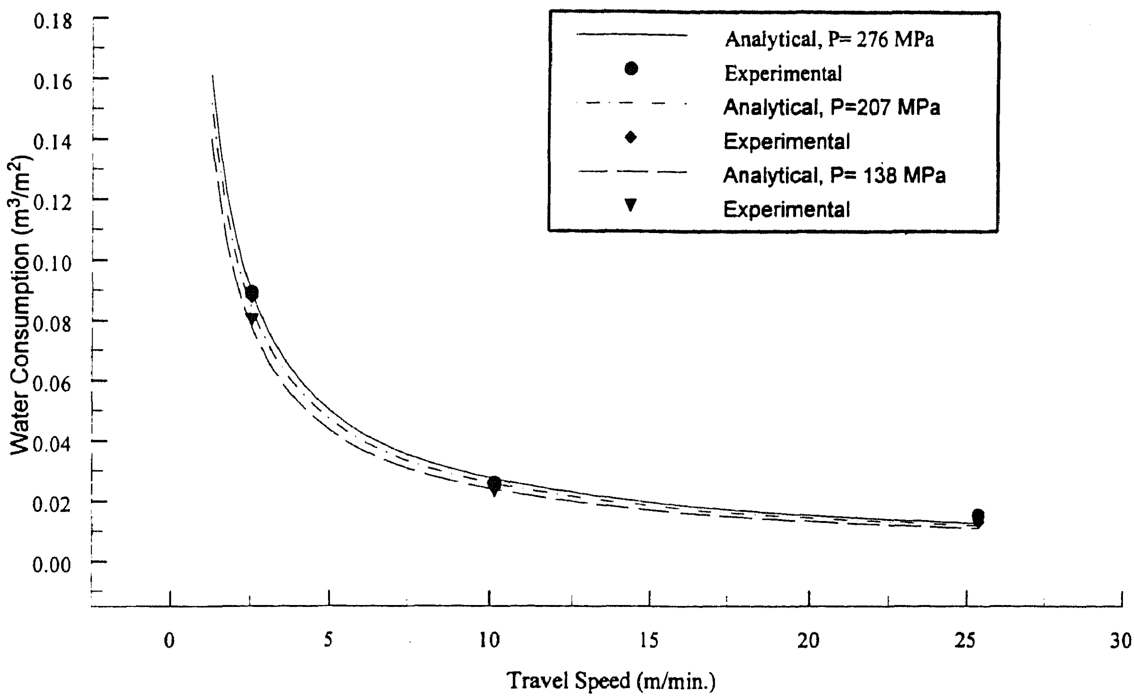

Fig. A.135 Water consumption vs. travel speed for oil-based paint removal with sapphire nozzle no. 7 under four different water pressures.

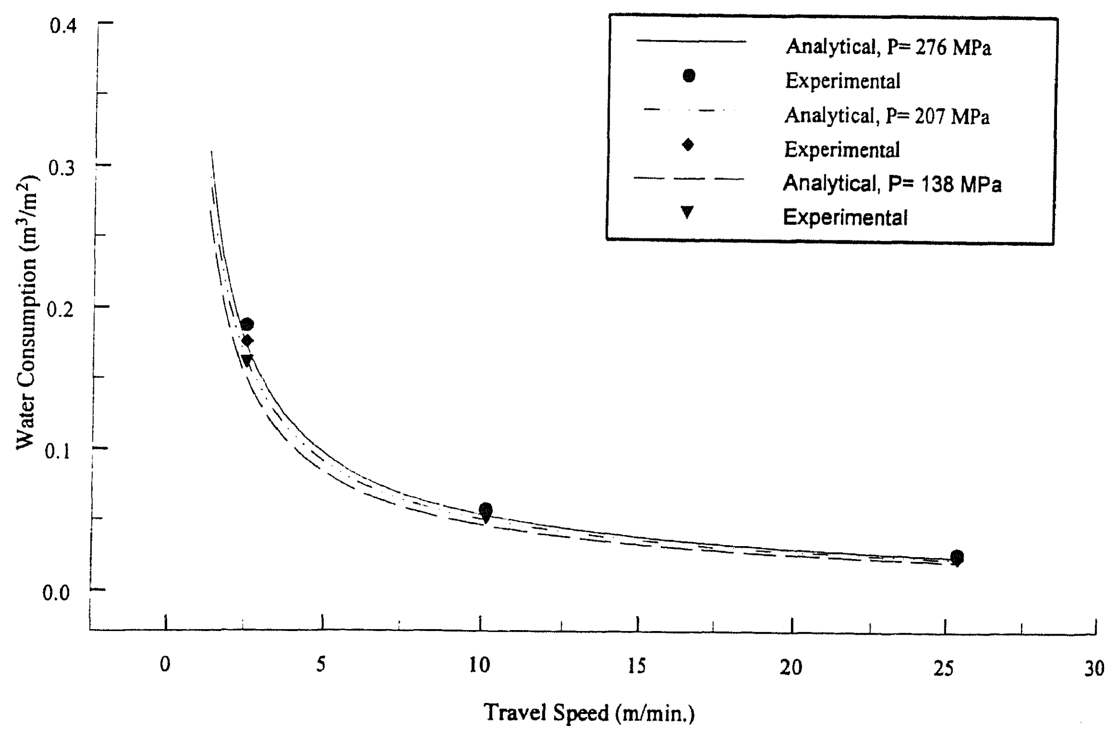

Fig. A.136 Water consumption vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 14 under four different water pressures.

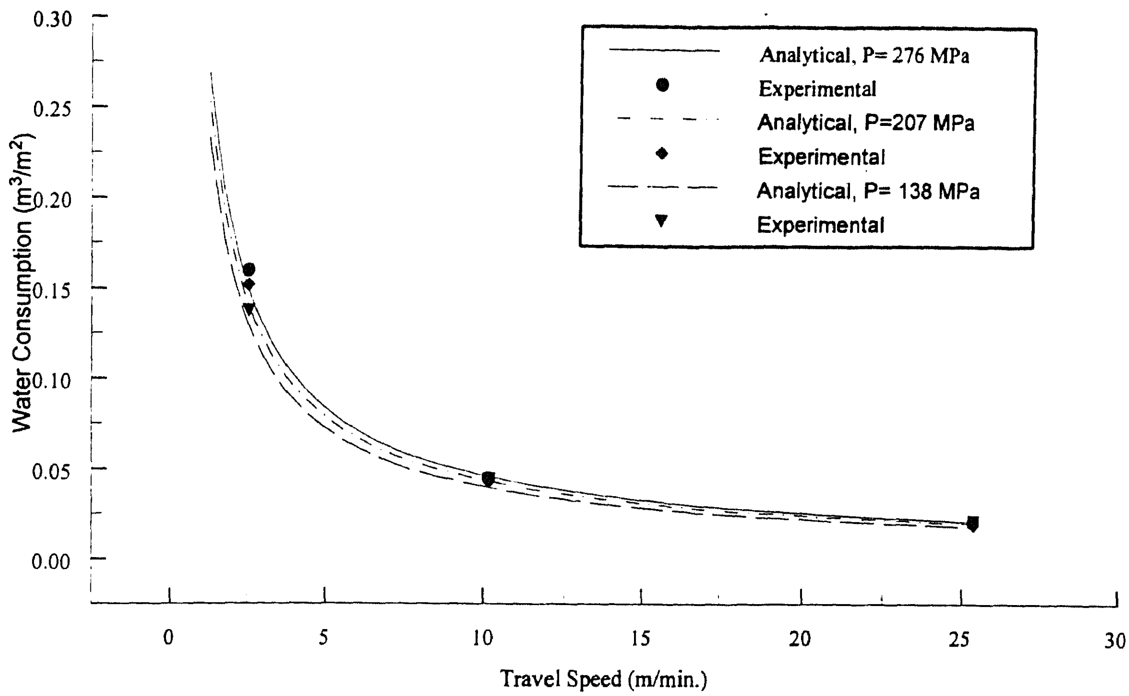

Fig. A.137 Water consumption vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 12 under four different water pressures.

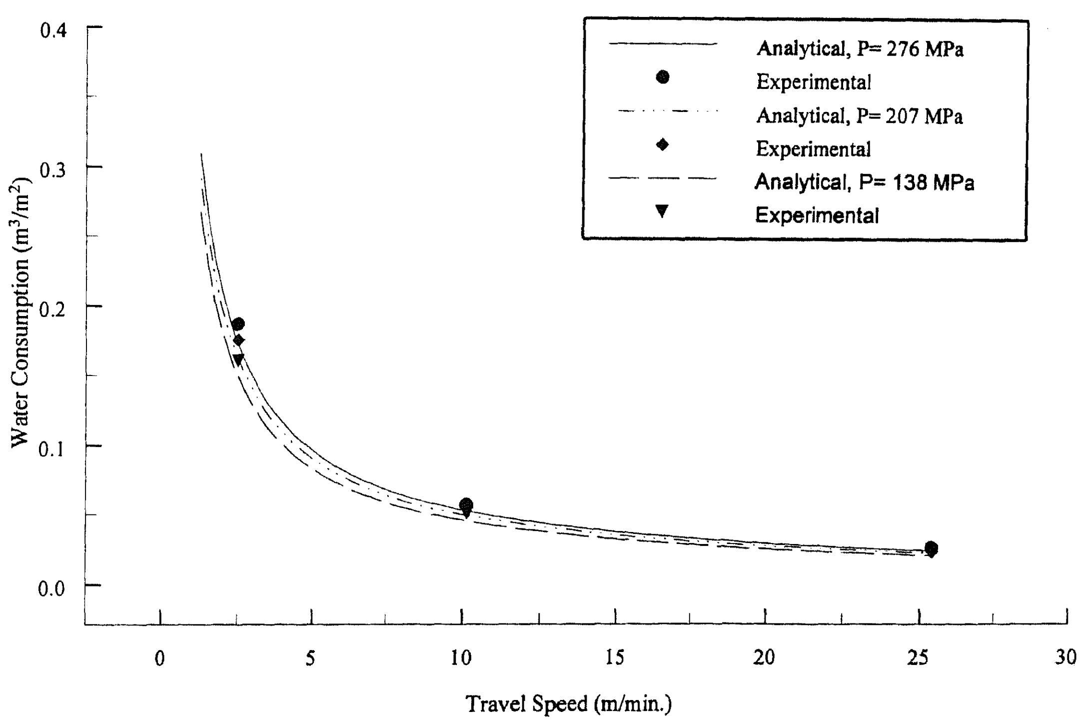

Fig. A.138 Water consumption vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 10 under four different water pressures.

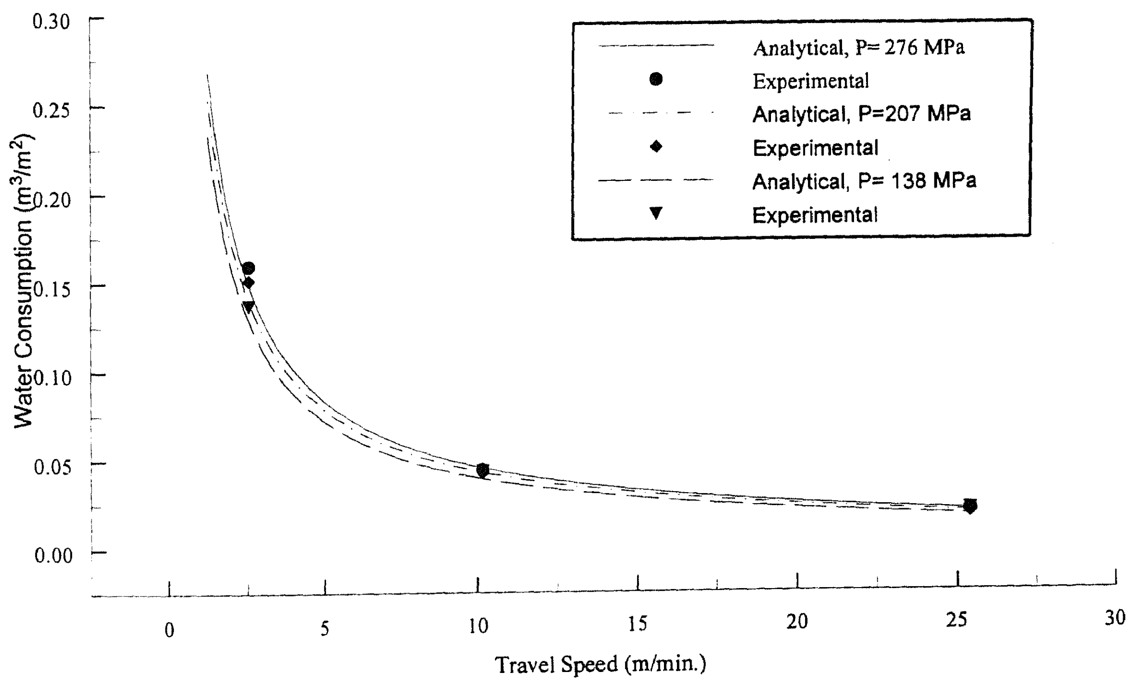

Fig. A.139 Water consumption vs. travel speed for epoxy-based paint removal with sapphire nozzle no. 7 under four different water pressures.

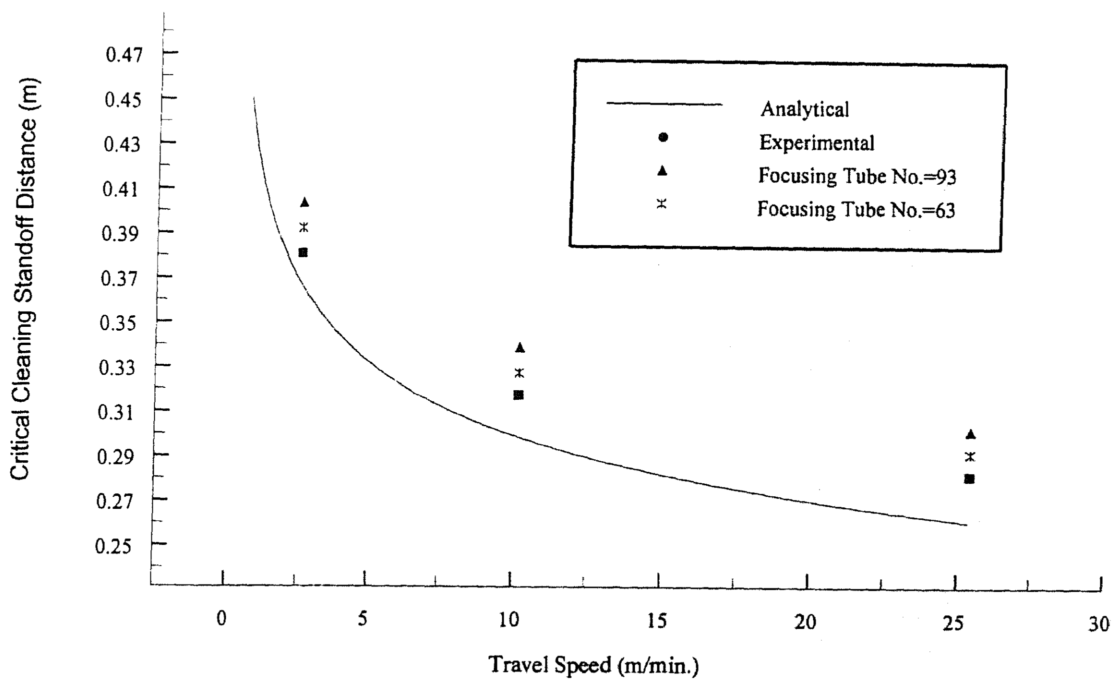

Fig. A.140 Critical cleaning standoff distance vs. travel speed for epoxy-based paint removal with and without focusing tube for nozzle no. 14 under two different water pressures.

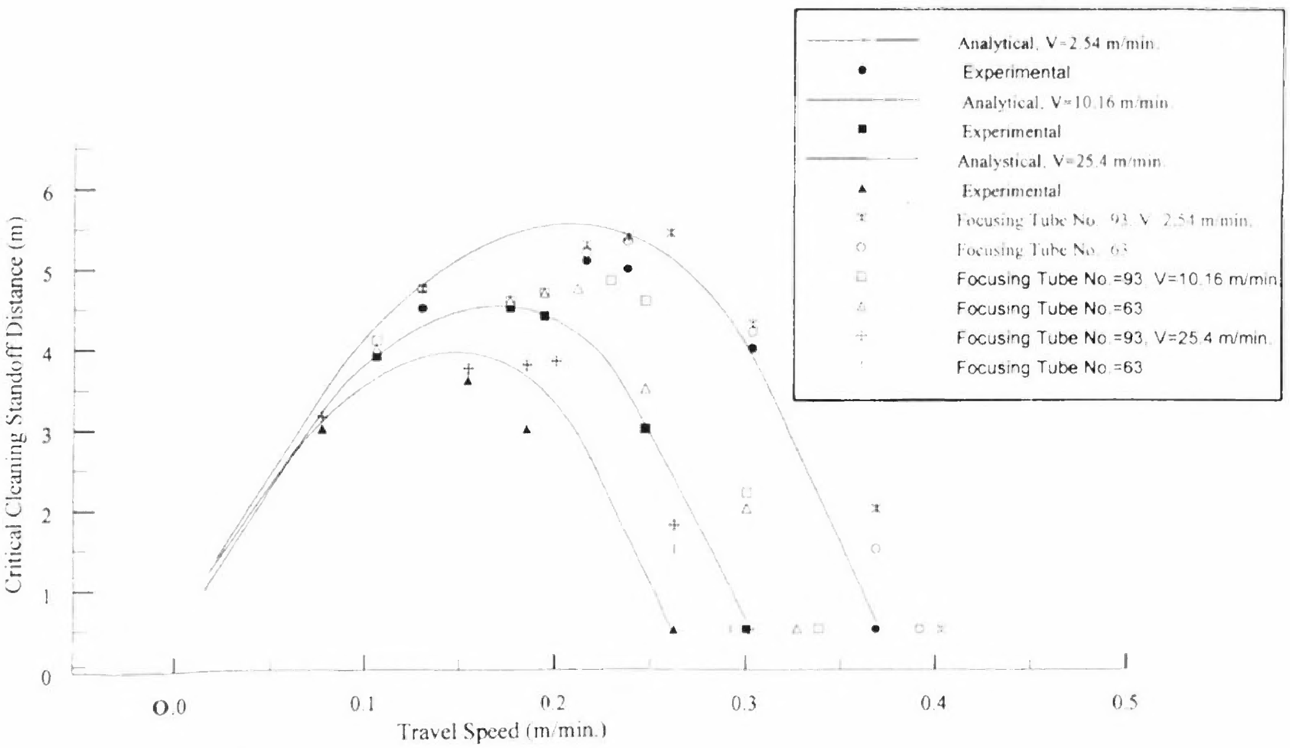

Fig. A.141 Cleaning width vs. standoff distance for oil-based paint removal with and without focusing tube for nozzle no. 14 under two different water pressures.

Fig. A.142 Micrograph of cracks, tearing at boundary of oil-based paint and substrate after waterjet coating removal.

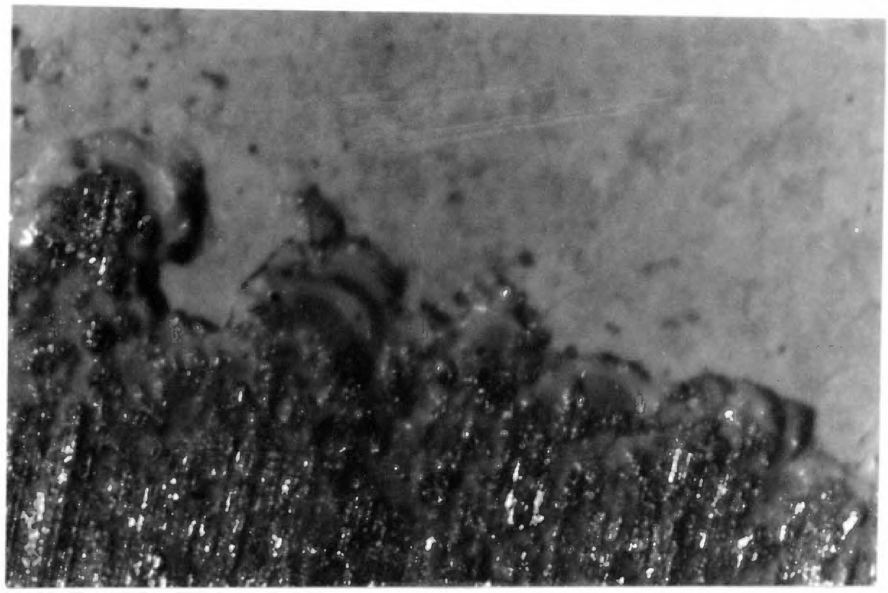

Fig. A.143 Micrograph of erosion at boundary of epoxy-based paint and substrate after waterjet coating removal.

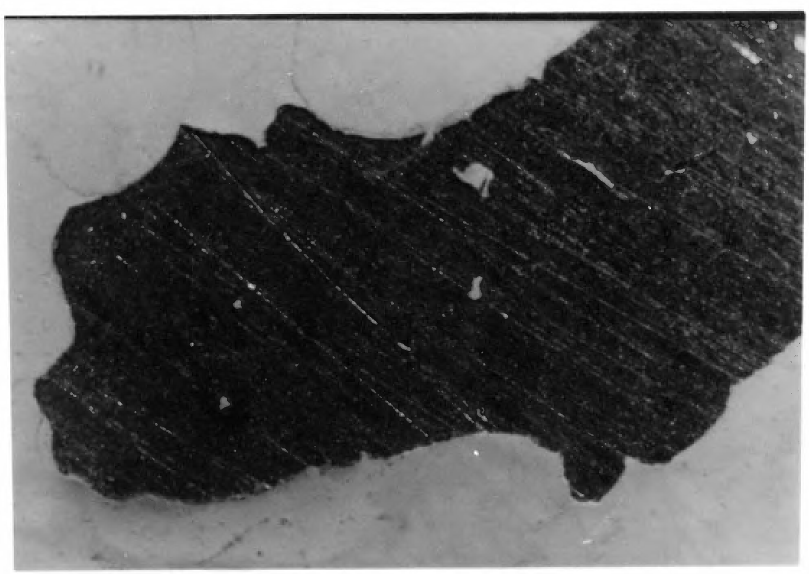

Fig. A.144 Micrograph of erosion at boundary of epoxy-based paint and substrate after waterjet coating removal (the coating was pretreated with surfactant FC-722, the smooth boundary with some cracks is shown).

Table A.1 Cleaning rate and water consumption for the removal of oil and epoxy paint at 311 MPa water pressure with two different sets of nozzles and focusing tubes

	Oil Paint			Epoxy Paint		
	Conventional Nozzle #10 & Focusing Tube #30	Modified Nozzle #12 & Focusing Tube #33	Spiral Nozzle #12	Conventional Nozzle #10 & Focusing Tube #30	Modified Nozzle #12 & Focusing Tube #33	Spiral Nozzle #12
Cleaning Rate (m^2/h)	6.86	8.782	14.33	6.1	8.226	13.716
Water Consumption (m^3/m^2)	—	0.01182	0.00725	—	0.01262	0.00757

Table A.2 Cleaning rate and water consumption for oil the paint removal with the modified sapphire nozzle no. 12 and focusing tube no. 63 at four different pressures

	Oil Paint			
	306MPa	204MPa	136MPa	68MPa
Cleaning Rate (m^2/h)	8.226	5.9436	5.6388	3.048
Water Consumption (m^3/m^2)	0.01262	0.01523	0.01415	0.01937

Table A.3 Water flow rate (LPM) as a function of pressure and nozzle size (measurement)

Pressure (PSI)	**Orifice Size** (IN/MM) 0.007 / 0.178	0.010 / 0.254	0.012 / 0.305	0.014 / 0.356
10,000			0.984	
20,000			1.39	
30,000	0.57	1.1	1.51	2.1
45,000	0.87	1.5	1.8	2.6

Table A.4 Water flow rate (GPM/LPM) as a function of pressure and nozzle size (recommended by FLOW INC.)

Pressure (PSI/BAR)	**Orifice Size** (IN/MM) 0.007 / 0.178	0.010 / 0.254	0.012 / 0.305	0.014 / 0.356
20,000 (1379)	0.145 (0.55)	0.295 (1.12)	0.425 (1.608)	0.578 (2.187)
30,000 (2069)	0.177 (0.67)	0.361 (1.36)	0.52 (1.97)	0.708 (2.68)
40,000 (2759)	0.204 (0.77)	0.417 (1.58)	0.601 (2.27)	0.818 (3.10)

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