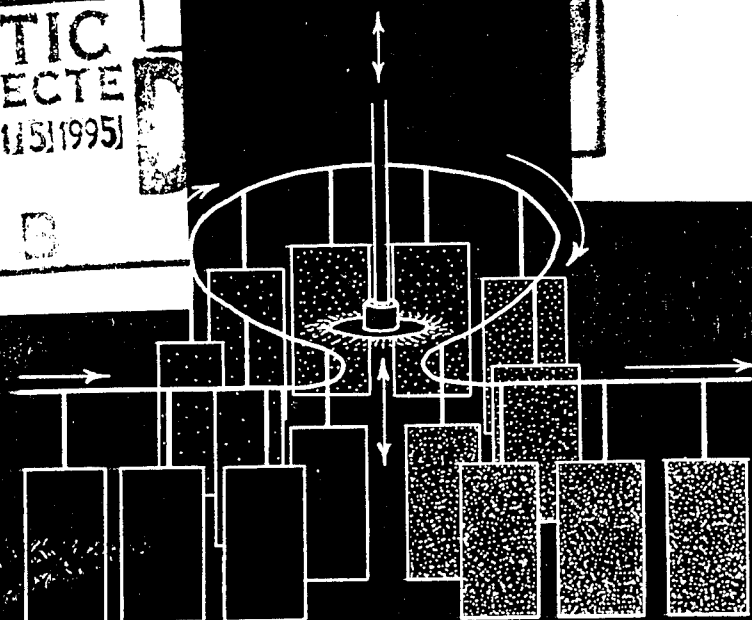


Electrostatic Powder Coating

DISTRIBUTION STATEMENT A

Approved for public release
Distribution Unlimited

DTIC
ELECTE
DEC 11 51 1995



PLASTEC
411875

DEPARTMENT OF DEFENSE
PLASTICS TECHNICAL EVALUATION CENTER
ARLINGTON, VIRGINIA 22204-6146

DISCLAIMER NOTICE



**THIS DOCUMENT IS BEST
QUALITY AVAILABLE. THE
COPY FURNISHED TO DTIC
CONTAINED A SIGNIFICANT
NUMBER OF PAGES WHICH DO
NOT REPRODUCE LEGIBLY.**

INACTIVE TERMINAL

>
NO CARRIER

Session disconnected.

*MSG DI4 DROLS PROCESSING-LAST INPUT IGNORED

*MSG DI4 DROLS PROCESSING-LAST INPUT IGNORED

*MSG DI4 DROLS PROCESSING-LAST INPUT IGNORED

*MSG DI4 DROLS PROCESSING - LAST INPUT IGNORED

-- 1 OF 1

DTIC DOES NOT HAVE THIS ITEM

-- 1 - AD NUMBER: D439308

-- 6 - UNCLASSIFIED TITLE: ELECTROSTATIC POWDER COATING,

--10 - PERSONAL AUTHORS: HUGHES, J. F. ;

--11 - REPORT DATE: , 1984

--12 - PAGINATION: 137P

--20 - REPORT CLASSIFICATION: UNCLASSIFIED

--22 - LIMITATIONS (ALPHA): APPROVED FOR PUBLIC RELEASE; DISTRIBUTION

-- UNLIMITED. AVAILABILITY: JOHN WILEY & SONS, INC., 605 THIRD AVE.,

-- NEW YORK, N. Y. 10158

--33 - LIMITATION CODES: 1

-- END

Y FOR NEXT ACCESSION

END

19951214 003

Electrostatic Powder Coating

ELECTRONIC & ELECTRICAL ENGINEERING RESEARCH STUDIES

ELECTROSTATICS AND ELECTROSTATIC APPLICATIONS SERIES

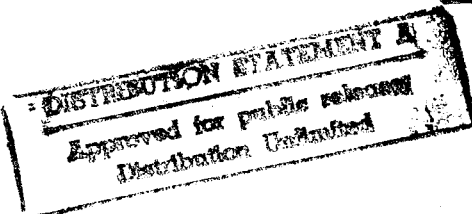
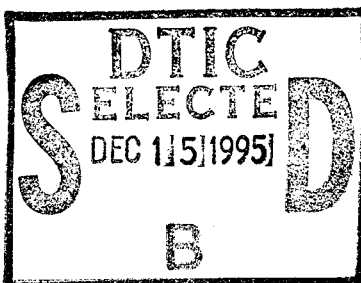
*Series Editor: Dr. J. F. Hughes, Department of Electrical Engineering,
University of Southampton, England*

1. Static Elimination
T. Horváth and I. Berta
2. Electrostatic Hazards in the Petroleum Industry
W. M. Bustin and W. G. Dukek
3. Electrophotography Principles and Optimization
Merlin Scharfe
4. Electrostatic Powder Coating
J. F. Hughes

| | |
|--|--|
| Accession For | |
| NTIS GRA&I | <input checked="checked" type="checkbox"/> |
| DTIC TAB | <input type="checkbox"/> |
| Unannounced | <input type="checkbox"/> |
| Justification | |
| <i>Printout enclosed</i> | |
| By <i>DTICAI</i> <i>MEMO</i> <i>2 Nov 95</i> | |
| Distribution/ | |
| Availability Codes | |
| Dist | Avail and/or Special |
| <i>A-1</i> | |

Electrostatic Powder Coating

J. F. Hughes, PhD, CEng, MIEE, FInstP
University of Southampton, UK



DTIC QUALITY INSPECTED



RESEARCH STUDIES PRESS LTD.

Letchworth, Hertfordshire, England

JOHN WILEY & SONS INC.

New York · Brisbane · Chichester · Toronto · Singapore

RESEARCH STUDIES PRESS LTD.
58B Station Road, Letchworth, Herts. SG6 3BE, England

Copyright © 1984, by Research Studies Press Ltd.

All rights reserved.

No part of this book may be reproduced by any means,
nor transmitted, nor translated into a machine language
without the written permission of the publisher.

Marketing and Distribution:

Australia, New Zealand, South-east Asia:
Jacaranda-Wiley Ltd., Jacaranda Press
JOHN WILEY & SONS INC.
GPO Box 859, Brisbane, Queensland 4001, Australia

Canada:
JOHN WILEY & SONS CANADA LIMITED
22 Worcester Road, Rexdale, Ontario, Canada

Europe, Africa:
JOHN WILEY & SONS LIMITED
Baffins Lane, Chichester, West Sussex, England

North and South America and the rest of the world:
JOHN WILEY & SONS INC.
605 Third Avenue, New York, NY 10158, USA

Library of Congress Cataloguing in Publication Data:

Hughes, J. F. (John Farrell), 1943-
Electrostatic powder coating.
(Electronic & electrical engineering research
studies. Electrostatics and electrostatic applications
series; 4)
Bibliography: p.
Includes index.
1. Plastic coating. 2. Spray painting, Electrostatic.
I. Title. II. Series.
TP1175.S6H84 1984 667'.9 84-10673
ISBN 0 86380 018 1
ISBN 0 471 90569 0 (Wiley)

British Library Cataloguing in Publication Data:

Hughes, J. F.
Electrostatic powder coating.—(Electronic &
electrical engineering research studies.
Electrostatics and electrostatic applications
series; 4)
1. Spray painting, Electrostatic
I. Title II. Series
667'.9 TT315

ISBN 0 86380 018 1
ISBN 0 471 90569 0 (Wiley)

ISBN 0 86380 018 1 (Research Studies Press Ltd.)
ISBN 0 471 90569 0 (John Wiley & Sons Inc.)

Printed in Great Britain

v

To, Christine, Carys and David.

Acknowledgements

Fundamental research into electrostatic powder coating has been actively carried out at Southampton University for a period of about 15 years. The author is indebted to the many colleagues who have contributed to this activity. A major part of the funding for this research was made available by the Science and Engineering Research Council, with generous contributions from many powder and equipment manufacturers. The advice and suggestions of Dr. J. R. G. Pude on mathematical modelling techniques are gratefully acknowledged.

Preface

Fundamental phenomena which govern the performance of powder coating equipment are often complicated and not always obvious in terms of practical implications on plant performance. Many scientific papers have been published in International Journals and conference proceedings, some of which will be referred to in the list of references and bibliography.

This monograph attempts to combine, in one concise volume, some of the most important practical implications drawn from in-depth research investigations. Mathematical relationships have been deliberately avoided whenever possible so as to introduce and familiarise the uninitiated reader with powder coating terminology and practical requirements. Nevertheless, the more experienced reader should find useful hints and design guides especially in the chapters on measurement techniques and system optimization.

The final chapter on future trends reviews some of the more recent innovations, and attempts to identify techniques that may contribute to future developments in powder coating technology.

Introduction

The distribution of a liquid in an even, thin protective layer over a surface has for many years been the method adopted for either protecting the substrate and/or enhancing its appearance. Distribution of the coating, or paint, is usually effected by one of three ways: brush, roller or spraying.

The apparent simplicity of the basic requirement is, however, misleading in many ways. Not only does the chemistry of the paint require meticulous attention, but so does the condition of the substrate onto which it is to be deposited. The interfacial conditions between substrate and paint have to be such that good adhesion is achieved when the solvents evaporate and the paint dries. This is a complicated chemical problem in itself, and will not be dealt with here. However, it is important to appreciate from the outset that 'painting' is a much more complicated and scientifically-exacting process than is generally presumed.

Liquid paint is widely used in manufacturing industries where invariably some type of coating is deposited on the finished product. Distribution of the paint by atomization into a fine aerosol lends itself very well to substrate coating, and numerous commercial coating systems are available. Some systems use air atomization while others adopt centrifugal forces for disruption of the continuous phase liquid into fine droplets. Numerous variations and

hybrids have been marketed, each with its own unique claim in terms of performance suitability to special requirements. A relatively recent innovation in coating has been the added sophistication of imparting electrical charge to the atomized paint particles. Again, this has been achieved in a number of ways including corona charging and induction charging, the net result being an improvement both in coating efficiency and evenness of coating thickness. Electrostatic painting soon became an established method of coating especially in the automobile and domestic appliances industries, with the now familiar 'wrap-around' characteristics contributing to an improvement in plant efficiency. Crop spraying of insecticides and herbicides has also benefited from electrostatic charging of liquid aerosol, which have produced an increase in the efficiency of deposition on vegetation and a decrease in the overall volume of chemical used ; important environmentally as well as cost advantage.

Probably the greatest limitation associated with wet paint spraying is that each particle or droplet has only one chance of achieving its objective - that of alighting on the workpiece. Particles that miss the workpiece are irretrievably lost in the capture system used in the coating booth. Sometimes the back walls of coating booths are water washed and the overspray is captured and discarded. In order to minimize overspray, and thus achieve maximum economic benefit, precise setting-up procedures for a gun-booth system are of paramount importance. These may be relatively straightforward, although tend to rely more on operating experience than scientific technique when a single type and size of workpiece is handled. In reality, of course, a typical coating line will be loaded with a variety of workpieces, changing from day-to-day or even from hour-to-hour. Under such conditions, it is difficult to see how gun systems can be maintained finely tuned to yield maximum performance.

It is the inability to reclaim overspray, together with the now high cost of petroleum-based solvents that has contributed more than any other factor to the development of dry powder paint alternatives. The elimination of a wet base, solvent or water, facilitates

reclamation of oversprayed paint - an important economic advantage which promises a potential 100% utilization of paint plus elimination of expensive solvents that are flushed-off and inevitably wasted. Thus electrostatic powder coating was conceived, and indeed has grown largely on these potential benefits. A variety of dry powdered paints were developed and these are now widely used in large quantities, making important inroads into areas where wet coating once dominated. The transition has not been easy, however, and many unforeseen difficulties were encountered - not least that of imparting unipolar electrical charge to solid isolated particles. Powdered products are notoriously difficult to handle compared to liquids, especially in terms of accurate metering and conveying through pipes. However, despite these difficulties, the advantages of using dry paint have outweighed the technical difficulties envisaged in the early stages of development. Early pistol application equipment was little more than a straight piece of pipe through which powder was blown, with a high-voltage corona charging electrode situated at the exit nozzle. This technique appeared to work reasonably well and became the model for all subsequent pistol development, such that many currently-used powder guns differ little from their early predecessors, being little more than corona points at the end of pipes. This approach may have been acceptable initially, but modern coating lines dictate a degree of sophistication which is difficult to find in most commercial arrangements. The constant search for better quality coatings coupled with higher deposition efficiency and faster line speeds has pushed most equipment to the limits of its performance capability. In order to achieve superior performance, the entire powder coating system has to be reappraised, and a more scientific approach must be adopted in relation to system optimization. It is no longer acceptable to point a pipe/corona point combination at a workpiece.

This monograph draws primarily from research work carried out at Southampton University over a period of about 15 years. Both fundamental and practically-orientated research programmes have been sponsored by the Science and Engineering Research Council, powder manufacturers and coating equipment manufacturers. Many aspects of

the work have already been published in technical journals and presented at International Conferences, and reference to these may be found throughout the text. In this single volume, some of the more important fundamental considerations are presented together with an attempt at highlighting the practical implications of experimentally-verified phenomena. A discussion of measurement techniques, followed by a critical review of some of the new and novel coating systems completes the text.

Table of Contents

| | Page No. |
|--|-------------|
| Acknowledgements | vii |
| Preface | ix |
| INTRODUCTION | xi |
| CHAPTER 1 PARTICLE CHARGING | 1 |
| Fundamental considerations | 1 |
| Corona charging of particles | 1 |
| Tribo or frictional charging | 8 |
| Induction charging | 12 |
| Ion wind | 15 |
| Back-ionization | 20 |
| Practical implications | 27 |
| CHAPTER 2 MEASUREMENT TECHNIQUES | 29 |
| Resistivity | 29 |
| Charge-to-mass ratio (q/m) | 40 |
| Gun potential and current | 47 |
| Electric field | 54 |
| CHAPTER 3 APPLICATION EQUIPMENT AND BOOTHS | 61 |
| Pistol applicators | 61 |
| Fluidised beds | 64 |
| Other systems | 69 |
| Coating booths | 82 |

| | Page No. |
|-------------------------------|-------------|
| CHAPTER 4 SYSTEM OPTIMIZATION | 91 |
| Booth and gun air | 96 |
| Gun voltage and current | 97 |
| Earthing | 99 |
| CHAPTER 5 FUTURE TRENDS | 105 |
| Equipment | 105 |
| Powders | 109 |
| Computer-aided modelling | 112 |
| SUMMARY | 115 |
| INDEX | 121 |

List of Illustrations

| Fig. No. | Page No. |
|--|-------------|
| 1.1 | 2 |
| 1.2 | 3 |
| 1.3 | 4 |
| 1.4 | 5 |
| 1.5 | 6 |
| 1.6 | 10 |
| (a) Non-frictional, energy level model. | |
| (b) Frictional, material transfer model. | |
| 1.7 | 13 |
| 1.8 | 14 |
| 1.9 | |
| 1.10 | 17 |
| 1.11 | 19 |
| 1.12 | 20 |
| (a) corona charged gun; | |
| (b) tribo-charged gun. | |
| 1.13 | 21 |
| 1.14 | 22 |
| 1.15 | 22 |
| 1.16 | 24 |

xviii

| Fig. No. | Page No. |
|--|-------------|
| 1.17 Double image arrangement for back-ionization evaluation. | 26 |
| 1.18 Energy measurements of back-ionization. | 26 |
| 2.1 Schematic of powder resistivity test cell. | 31 |
| 2.2 Powder resistivity test meter. | 34 |
| 2.3 Electric field measurement on charged powder layer. | 35 |
| 2.4 A typical exponential decay plot of electric field versus time. | 36 |
| 2.5 Charge conduction paths in packed powder sample. (a) Bulk conduction; (b) Surface conduction. | 37 |
| 2.6 Method for measuring surface resistance. | 39 |
| 2.7 Simple Faraday cup arrangement. | 42 |
| 2.8 Schematic of ion-trap in powder stream. | 42 |
| 2.9 Irrigated grid device for absolute measurement of q/m . | 43 |
| 2.10 Powder coating test-set. | 46 |
| 2.11 Schematic of resistor chain voltage probe. | 49 |
| 2.12 Electrostatic voltmeter. | 51 |
| 2.13 Rotating vane type field mill. | 55 |
| 2.14 Modified field mill head with air purge facilities. | |
| 2.15 Field intensification due to presence of field mill in charged cloud. | 58 |
| 3.1 Schematic of simple fluidised bed coater. | 65 |
| 3.2 Typical commercial fluidised bed system. | 66 |
| 3.3 Inherently safe fluidised bed. | 68 |
| 3.4 Simplified details of pistol applicators. (a) Conventional corona charging. (b) Low voltage corona charging. | 70 |

| Fig. No. | | Page No. |
|-------------|--|-------------|
| 3.5 | Detail of low voltage gun. | 73 |
| 3.6 | Schematic of corona-assisted tribo gun. | 75 |
| 3.7 | Cyclo-Gun. (a) Complete system; (b) Detail of gun nozzle. | 77 |
| 3.8 | Typical air-less blade-coater. | 79 |
| 3.9 | Typical powder disc system. | 80 |
| 3.10 | Conveyor loop with disc coater. | 81 |
| 3.11 | Electric field lines configuration between gun and workpiece. (a) Earthed metal booth. (b) Electrically insulating booth. | 84 |
| 3.12 | Simplified schematic of Volstatic Super Coater system. | 85 |
| 3.13 | Schematic cross-sectional view of electric curtain tile | 87 |
| 3.14 | Schematic of electric curtain booth. | 89 |
| 3.15 | Schematic of bottle coater using electric curtain booth panels. | 90 |
| 5.1 | Irrigated grid showing effects of back-ionization on layer deposition. (a) Dry grid. Back-ionization. (b) Irrigated grid. No back-ionization. | 108 |
| 5.2 | Typical flow diagram for powder coating programme. | 113 |

CHAPTER 1

Particle Charging

FUNDAMENTAL CONSIDERATIONS

The prime requirement of all powder coating systems is that of imparting electrical charge, usually unipolar, to individual particles. In order to complete the process, the charged particles then have to be manipulated such that they alight and adhere on what is usually a grounded metal substrate. The movement of the particles between the charging station and substrate is usually governed by either electrical or mechanical forces, or a combination of both. Electrical forces are created by the interaction between the charged particles and the electric field between substrate and gun, while mechanical forces are those resulting from air being driven through the gun. As will become clear later, these two forces are of paramount importance in terms of the overall behaviour and performance characteristics of individual coating systems.

When considering the basic requirement of imparting charge to a particle, it helps to simplify the situation by assuming the particles are spherical and that most paints will be electrically insulating; that is, assume a bulk resistivity in excess of $10^{13} \Omega\text{m}$. So how do electrically isolated, highly insulating particles become charged?

CORONA CHARGING OF PARTICLES

This is perhaps the most widely used method of particle charging in both pistol and fluidised bed coaters. In its simplest embodiment, the charging electrode may be a sharp pointed needle-like electrode,

or a fine gauge wire. The electrode is connected directly, or via a high resistive load, to a high voltage generator. A direct result of the geometry of the electrode, as shown in Figure 1.1 for a pointed needle, will be an enhancement of the electric field at the point.

For a given applied potential, the smaller the radius of curvature of the needle-point, then the greater will be the local enhancement of electric field. If the combination of needle geometry and potential is sufficient to create a local electric field of

about 3 MV/metre, then electrical breakdown of the air itself in the vicinity of the point will occur. This breakdown, or discharge, usually manifests itself as a relatively low energy continuous process rather than a short lived spark. It is this continuous discharge, or corona discharge, that is ultimately responsible for particle charging. The mechanisms involved are complicated and will not be discussed here. Assuming that the point electrode was subjected to a high voltage of negative polarity, then the local discharge, or ionization of the air, results in charge separation and the creation of unipolarly charged molecules, or ions. A simplified energy level diagram representation of the electrode/air interface is shown in Figure 1.2. The high electric field appearing at the electrode surface has the effect of lowering the energy necessary for electrons to escape from the confines of the metal electrode.

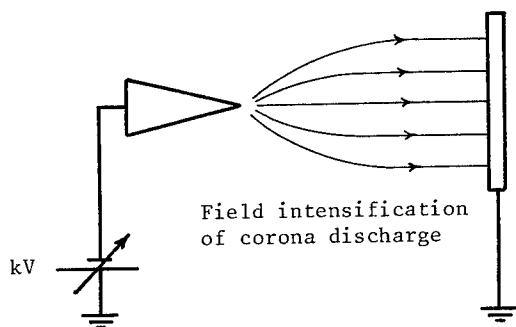


Fig. 1.1 Field intensification at a sharp point.

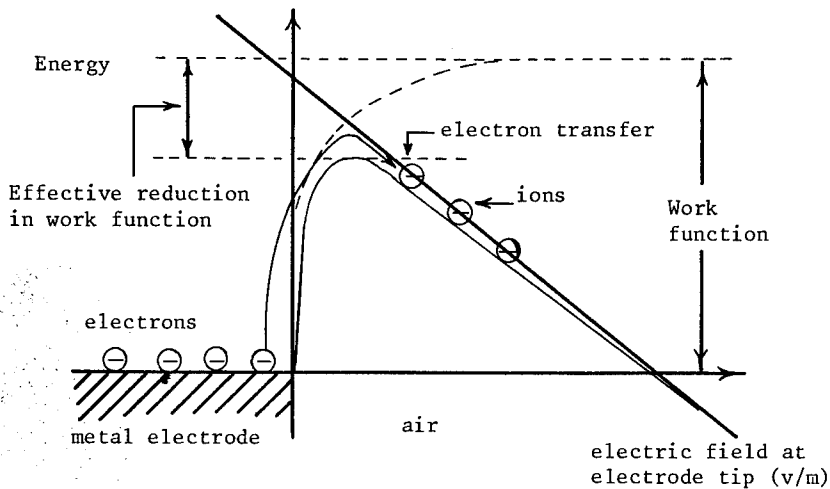
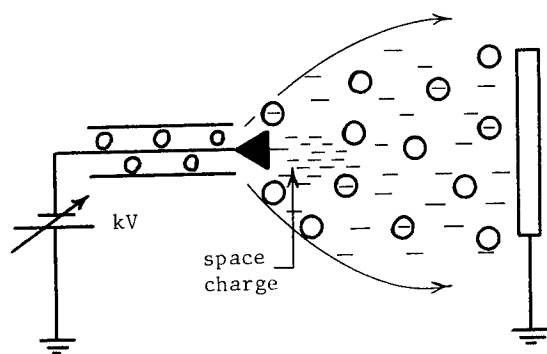


Fig. 1.2 Simplified energy level model for electron injection.

Almost instantly after transition from metal to air, the high mobility electrons are rapidly trapped by air molecules creating a low mobility negative ion.

It is these slower moving negative ions, which drift away from the charging electrode under the action of the electric field, that are ultimately responsible for particle charging. The ions are created at the gun nozzle, and tend to accumulate near the electrode creating a space charge before drifting towards the workpiece. This space charge usually occurs when the rate of ion creation exceeds the rate at which they drift away from the discharge region. Powder particles emanating from the gun nozzle travel through this space charge, picking up ions on their flight between gun and workpiece. Figure 1.3 illustrates schematically the situation that might exist in a typical gun system.

The situation is already becoming much more complicated than originally envisaged. In reality, the gun projects not one, but three species of 'particles' at the workpiece. Not just charged paint particles, but also uncharged paint particles and negative ions. Later, we shall see how this complicates the fundamental understanding of the powder coating process, and raises many difficulties both



- Uncharged powder particles
- ⊖ Charged powder particles
- Negative ions

Fig. 1.3 Corona charging in pistol applicators.

in terms of realising high quality coatings and achieving meaningful interpretation of measurements on commercial systems. The way by which the ions actually attach themselves to individual particles is not clearly understood, and in-depth fundamental research programmes have attempted clarification of this mechanism.¹

Most commercial powder paints are complicated composites, and the question arises as to where or to what does each individual ion attach itself on the particle surface. With most paints being electrically very resistive, it is difficult to envisage how ionic attachment is achieved at all; bearing in mind that ionic attachment will only occur when a suitable accepting site is available on the particle surface. In the case of negative ions, this accepting site might be an electronegative impurity or component in the paint formulation. Ionic trapping may be purely mechanical. Whatever the mechanism, efficient deposition of ions on each particle will by no means be easy. The high electrical resistivity is in itself a major constraint to efficient particle charging. Consider the situation represented

in Figure 1.4.

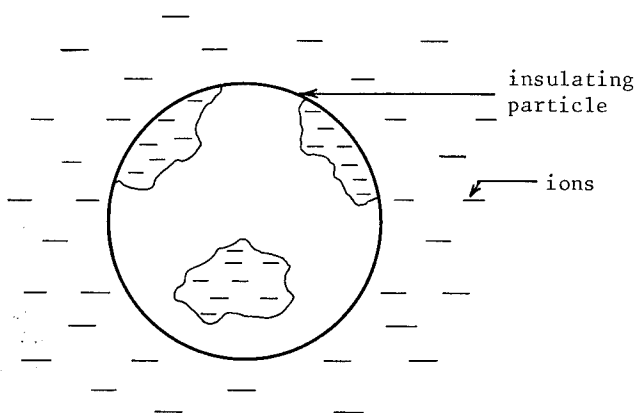


Fig. 1.4 Ionic charging of electrically insulating particles.

As the particles and ions drift towards the workpiece at different velocities, it is feasible that some ionic collection will occur as a result of direct impaction with the particle surface. Assuming that the ions, on impaction, are retained on the surface, then each ion is 'locked' into position at the exact point of impaction. Since the surface resistance of the average particle will be high, then no surface conduction will occur over the surface as a result of particle re-distribution - unlike conducting particles where the charge density of the entire surface of a spherical particle will be constant due to surface migration. For insulating particles, therefore, the situation depicted schematically in Figure 1.4 might well be the norm. That is, particles arriving at the substrate with uneven surface charge distribution in the form of immobile charge islands. With this inability to redistribute over the particle surface, it is not difficult to appreciate the fundamental difficulty associated with efficient charging of insulating particles.

The model suggested here for ionic charging of isolated particles is of course oversimplified, but nevertheless serves a useful purpose in terms of understanding the fundamental difficulties associated

with efficient ionic capture.

For complete and accurate modelling of such a situation, other considerations need to be taken into account. For example, an isolated particle in an ionic cloud will tend to accumulate ions until its potential equals that of its surroundings. In an ideal spherical model situation, it might be acceptable to assume that ionic motion towards the particle will be uniform in all directions, and therefore the surface charge distribution will be uniform. This may be so in a situation where the particle may be perfectly motionless - a condition hardly likely to occur in reality in a gun system. Another important consideration is the fact that, associated with all isolated particles, there will be a maximum surface charge density which cannot under any circumstances be exceeded. This is known as the Pauthenier limit, and is of prime importance when modelling particle charging situations and evaluating the charging efficiency of various systems.² This will not be described in detail, but a superficial appreciation of the mechanism would be useful for future reference. Consider a similar situation to that depicted in Figure 1.5, and assume that all regions of the particle surface are charged.

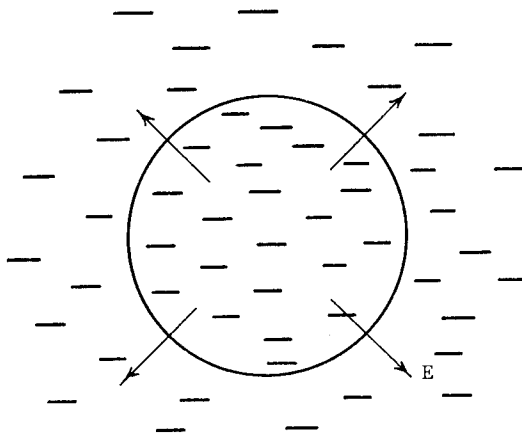


Fig. 1.5 Maximum surface charging of isolated particle.

Under normal circumstances, the movement of ions onto the surface will cease when the potential of the particle equals that of its surroundings. An electric field, E, will be created as a result of this surface charge, and will be the field at the interface between the particle and its surroundings, as shown in Figure 1.5. With continued increase in charge collection, E will increase until a value is reached which corresponds to a situation where no further transport of ions onto the particle will be possible. This limiting value of surface charge, the Pauthenier limit, may be expressed mathematically by the following relationship:-

$$Q = 4\pi \epsilon_0 a^2 B E \quad (1)$$

$$\text{where } B = 1 + 2 \frac{(\epsilon_r - 1)}{(\epsilon_r + 1)}$$

and ϵ_0 = permittivity of free space = $8.854 \times 10^{-12} \text{ F.m}^{-1}$.

ϵ_r = relative permittivity of powder particle.

a = radius of particle.

E = electric field which particle is subjected to.

For a spherical particle its mass 'm' will be:-

$$m = \frac{4}{3} \pi a^3 \rho \quad (2)$$

where ρ = density of particle.

So, the charge to mass ratio, q/m, will be:-

$$\frac{q}{m} = \frac{4\pi \epsilon_0 a^2 B E}{\frac{4}{3} \pi a^3 \rho} = \frac{3 \epsilon_0 B E}{\rho a} \quad (3)$$

Substituting the following typical values of:-

$$\epsilon_r = 2, E = 10^6 \text{ Vm}^{-1}, a = 50 \times 10^{-6} \text{ m}$$

$$\epsilon_0 = 8.854 \times 10^{-12} \text{ F.m}^{-1} \text{ and } \rho = 10^3 \text{ kg.m}^{-3}$$

into equation (3) gives the maximum value of q/m at the specified field as:-

$$\left(\frac{q}{m} \right)_{\text{max}} = 8.8 \times 10^{-4} \text{ C/kg}.$$

So far, we have considered only negative charging of isolated particles. If positive charging is used then previous statements relating to charge behaviour and Pauthenier limit are still valid; but the actual mechanism of the corona discharge at the electrode point will be different. With positive high potential applied to the electrode, electrons will now have to be stripped from neutral air molecules thus creating positive ions, which in turn migrate towards the earthed workpiece and interact with powder particles in a manner identical to that of negative ions. The electrons are rapidly collected by the charging electrode. As for negative ions, both the mechanism of capture on the surface of each particle, and the mechanism of ionic attachment - electrical, mechanical or a combination of both - are unclear. After deposition of the particles on the workpiece, the behaviour of the coating will differ according to whether the particles are negatively or positively charged. This important factor is discussed later in relation to back-ionization.

TRIBO OR FRICTIONAL CHARGING

One of the earliest electrical phenomena to be documented and investigated was associated with the fact that when two different materials were in contact and subsequently separated, they appeared to display characteristics which implied that electrical charge had been exchanged during their period of contact. This phenomenon is now widely experienced in everyday life, especially with the advent of electrically insulating man-made fibres. Electrical charging and sparking associated with nylon shirts and carpets, for example, are common occurrences. While fundamental mechanisms relating to this charge exchange will not be discussed in detail, a superficial understanding of the mechanisms involved^{3,4} will be attempted.

In the case of two different solid materials brought into contact, the usual result is an imbalance in charge between the two molecular layers that are in intimate contact. Depending on the crystallographic and chemical structure of the two materials, re-organisation of charge will occur across the interface in an attempt to restore electrical balance. This migration of charge will usually be by

electronic conduction or transfer, and the degree and direction of migration will be dictated primarily by what is known as the Tribo-electric Series.⁵ This model uses the concept of the energy level diagram similar to that shown in Figure 1.2. That is, the relative positions of electronic energy levels in each material, when brought into contact, determine the direction in which electronic transfer will take place. Many of the most common materials used in electrical engineering have been evaluated in terms of their position in the tribo series, which facilitates a degree of predictability in terms of charge exchange behaviour. For materials which have not been evaluated, however, predicting the direction of electronic transfer when in contact with a different material will require some conjecture.

All materials, solids and liquids, display this charge exchange phenomenon. Charge exchange will occur across all solid/solid, solid/liquid and liquid/liquid interfaces. For many materials, the occurrence of charge re-organisation at the interface will not be obvious. This is primarily because most materials are electrically conducting; thus charge transfer across the interface occurs simultaneously with relaxation and neutralization of the charge by virtue of the conductivity of the material. Only when the materials are electrically insulating does the charge exchange result in the long-term creation of unipolar charge either on the surface of solids, or within the bulk of liquids. In fuel handling systems, this can be especially hazardous when electrically insulating and highly flammable hydrocarbon fuels are pumped at high velocities, for example in aircraft refuelling systems. Due to the charge exchange mechanism, unipolarly charged fuel may accumulate in the fuel tanks, resulting in high energy discharges leading possibly to fires and explosions.⁶ Since this is not relevant to the present discussion, the emphasis will be on charging of solid surfaces.

Tribo-charging is a prime example of an electrical phenomenon which is not completely understood. Much research has been devoted in an attempt to produce a more precise model of the interface

phenomena. The complex models proposed are beyond the scope of the present discussion, but it is relevant that at least two mechanisms may be responsible for charge exchange across a solid interface. This is the electronic transfer mechanism associated with the electronic energy levels, and this model is the one primarily used for non-frictional contact. In the event of a sliding, or frictional contact, however, an additional mechanism might be involved. During frictional contact, it has been established that some degree of material transfer may actually occur from material to material. A direct result of this will be a change in the net charge on each surface, leading to an effective charge exchange across the interface. Probably, in the case of particle charging in a coating system, a combination of these two mechanisms will be responsible for some degree of tribo-charging as the powder is delivered from the hopper, through the feed pipes and into the gun itself. Figure 1.6 illustrates a much simplified model of the way in which the two main charge exchange phenomena can result in particle charging.

In Figure 1.6(a), assuming the energy levels associated with trapped electrons are higher in Material 2, than Material 1, then electronic transfer will occur from 2 into 1 until an effective equalisation of the upper energy levels is achieved.

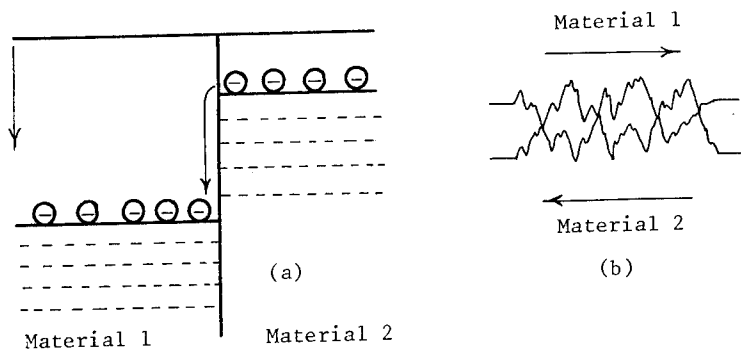


Fig. 1.6 The charge exchange mechanisms across two solid interfaces.
 (a) Non-frictional, energy level model.
 (b) Frictional, material transfer model.

In this case, material 1 would retain a net negative charge while material 2 would retain an equal and opposite net positive charge. This energy level model must be used with caution, however, since it is a model which has been developed specifically for semiconductor materials, and relies on long-range crystallographic order for meaningful interpretation. Most insulating materials display only short-range crystallographic order, and therefore the energy level model can only be truly representative of the material behaviour over short distances within its bulk. Accepting this restriction, then it is nevertheless a useful model which facilitates an understanding of the basic mechanism of charge migration across an interface.

Figure 1.6(b) is a schematic representation on a molecular scale of the interface between two materials. True contact is only achieved between the high-spots, or peaks, on the actual surfaces. Assuming relative movement between these two surfaces, it is not difficult to envisage how the high spots may be sheared and some degree of material interchange can occur between the two surfaces.

In powder coating, most of the powder paints used are highly insulating; if tribo-charge exchange mechanisms exist, then it is very likely that their effect will be noticeable. In other words, the powder particles will retain their charge, and likewise, the inside surfaces of the guns and feeding hoses will retain an equal and opposite charge. Almost all commercial coating systems will include a component of tribo-charging; it is very unusual to find systems that do not tribo-charge to some extent. Some systems rely entirely on tribo-charging, and these will be reviewed in detail later.

By its very nature, tribo-charging is notoriously unpredictable and its characteristics can vary according to the material and the ambient conditions - especially relative humidity. Even in corona charged guns, an appreciation of the tribo-charging component can be important in terms of overall gun behaviour. When tribo-charging is high, then the polarity of the corona charging should be chosen so that the two mechanisms interact constructively. However, other

factors need to be considered when choosing polarity; these will be discussed later together with the implications of back-ionization.

In summary, the result of blowing insulating powder particles through a gun is retention by the particles of a net electrical charge - either positive or negative. Some commercial guns utilise this phenomenon, relying entirely on tribo-charging to effect particle charging. In relation to the coating process, there is a subtle difference between corona charged and purely tribo-charged particles. In Figure 1.3, three species of 'particles' are identified. In tribo-charged guns, no free ions are created, resulting in a system producing only two species: charged particles and uncharged particles. Generally, there will be no high potential at the end of the gun, and the subsequent particle migration mechanism and trajectories from gun to workpiece will be quite different for corona and tribo-charged guns.

Figure 1.7 illustrates schematically the tribo counterpart of the corona system illustrated in Figure 1.3.

An equal and opposite charge to that of the particles will be deposited on the inside wall of the gun barrel. With continued use, this will have detrimental effects on the long-term charging characteristics of tribo-guns (see Chapter 3). The deposition field is primarily that due to the charged powder cloud itself, and particle trajectories will be dictated more by the air flow than by electrical effects.

INDUCTION CHARGING

There is a third method of charging which is perhaps not as familiar as corona and tribo-charging, although it is widely used in liquid charging systems. This is known as the mechanism of charging by induction, or influence. Generally, the technique requires the particle to be charged, be it liquid or solid, to be relatively conducting compared to the usual powder paint materials; and this is probably why induction charging has not featured as an important alternative in powder coating. For materials of resistivity below

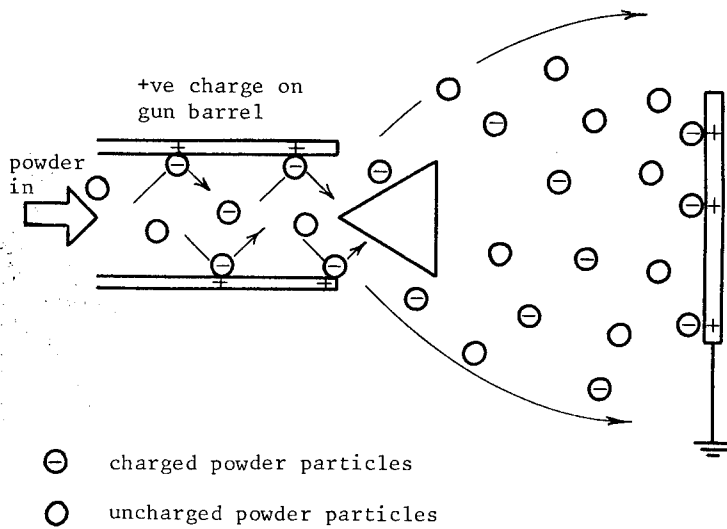


Fig. 1.7 Tribo-charging of insulating particles.

about $10^8 \Omega \cdot m$, electronic conduction through the bulk of the material may be achieved relatively easily. That is, the material is no longer a good insulator and will readily acquire charge if in contact with an electrically energised electrode. Figure 1.8 illustrates schematically the mechanism by which particles may be charged in this way.

When the particles are in contact with the feed electrode, they acquire charge of the same sign as the electrode. On breaking contact, the particles will retain their charge, and will be carried towards the workpiece under the combined effects of electric field and gun air. Since charging will be primarily by contact or induction, there will be no generation of free ions, and the system will therefore behave very much like a tribo-charged gun. Charging will be very efficient, as particles not even in direct contact with the high voltage electrode will still acquire charge. That is, under

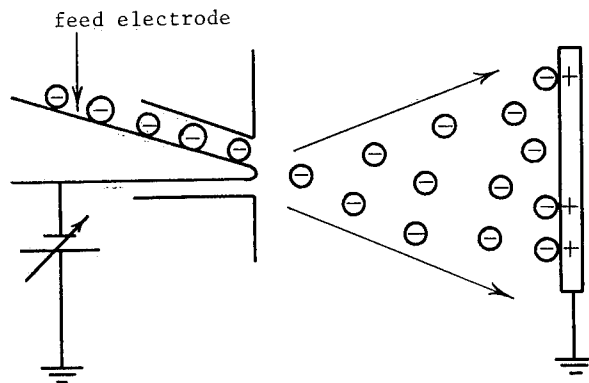


Fig. 1.8 Charging of conducting particles by induction.

normal operating conditions, powder will probably flow over the charging electrode in a multi-layer stream. The uppermost layers of powder will acquire charge from the layer immediately below, and so on, until the layer in contact with the charging electrode is reached - unlike the tribo gun where each individual particle has to contact the gun surface in order to effect charge exchange.

Although the charging characteristics of conducting powder might be very attractive, it must be appreciated of course that such high conductivity will be totally unacceptable in terms of good adhesion to the workpiece. A contradiction exists in terms of ideal powder resistivity for good electrostatic performance. At the charging station, resistivity should be as low as possible in order to effect efficient charge exchange. Once charged, however, the resistivity should be as high as possible in order to ensure adequate particle adhesion to the substrate prior to curing. A compromise should

ideally be sought, where both requirements are fulfilled at least to give acceptable overall performance. This same constraint appears to exist also in other applications requiring particle charging and manipulation, notably electrostatic precipitation and electro-photography.

In powder coating there would appear to be little evidence that powder manufacturers are considering electrical resistivity as an important parameter in the formulation of their final product. Powders destined for use in electrostatic equipment have not in general been optimized in terms of their electrical characteristics and their suitability for accommodating charge. Further improvement in coating efficiency and behaviour is dependent on the availability of more electrostatically-tailored powders.

ION-WIND

In understanding the behaviour of charged particles in a typical coating system, the effects of free ions on system behaviour as well as the practical implications on overall coating quality are important. The effects of ion wind are generally confined to systems with external corona charging, typical of that shown in Figure 1.3. The trajectories of the uncharged particles will be dictated primarily by the air flow pattern, while for the charged particles and ions an additional force, that of the electric field between gun head and workpiece, will also contribute to particle behaviour. It is the interaction between the movement of charged particles and ions and the electrically neutral air in which they are suspended which in turn gives rise to an additional component of forward velocity. Since the ions are much smaller and have a much higher mobility (mobility = velocity per unit field, $m^2 \cdot v^{-1} \cdot s^{-1}$) than the paint particles, then their motion between gun and workpiece is very rapid. It is the collection of ions on the workpiece which accounts for the main current path between gun and workpiece. During their free-flight period, the ions will collide repeatedly with neutral air molecules. Momentum exchange will take place, resulting in an induced motion of the air itself in the same direction as the ions.

This electrically induced movement of air is known as the ion-wind; an additional component of air velocity to that created by the gun air supply.⁷ In some systems, the ion-wind air velocity can be comparable in magnitude to the gun air (up to 2m.s^{-1}), and must be considered when overall performance is to be evaluated. Figure 1.9 illustrates schematically how air motion is induced by ionic transfer.

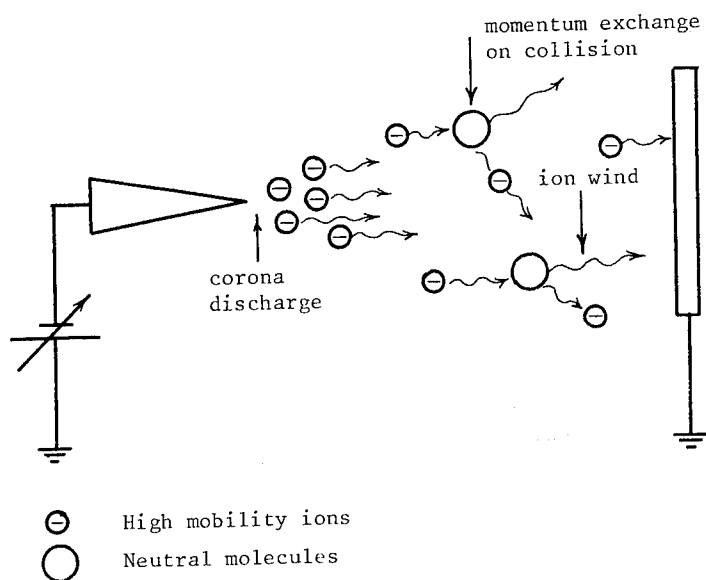


Fig. 1.9 Ionic-induced air movement.

Ion wind will invariably be created in the vicinity of unipolar corona electrodes, and its effects may readily be experienced as local cooling on the palm of the hand or deflection of a wind vane situated near the electrode. This momentum sharing, or ion-drag, effect has been put to useful purposes in other areas of engineering, especially in applications requiring accurate low velocity pumping of

liquids. Injection of charge into a liquid, together with the application of high field, has resulted in the now familiar ion-pumps⁸: a useful innovation if moving parts present in a conventional pump could detrimentally affect the product being handled.

The implications of ion-wind are important, and should not be underestimated. Even in so-called air-less guns, there will normally be a substantial component of forward air velocity which will dictate to a large extent just where each particle will alight on the workpiece. For example, the traditional schematic representation of the performance of an electrostatic gun system is similar to that shown in Figure 1.10. The electric field lines shown are said to describe both the trajectories of charged particles, and the way in which coating of the rear, or shadow area, of the workpiece becomes possible as a result of wrap-around.

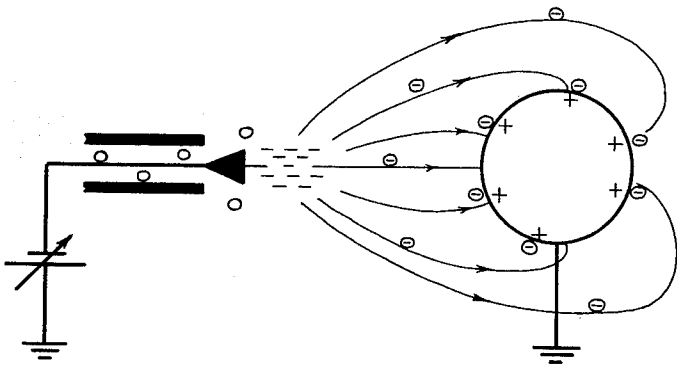


Fig. 1.10 Typical electric field line configuration

Charged particles will tend to follow the lines of electric field enabling complete coating with just one gun. This theoretical model would accurately describe typical trajectories. However, in reality, since the combined effects of gun air and ion-wind are substantial,

the actual particle trajectories will be very different to that shown in Figure 1.10. It has been shown that pneumatic forces predominate for most of the particle trajectory between gun and workpiece, and only when the charged particle is within about 2 cm of the surface of the workpiece do the attraction forces between it and its image charge begin to take over.⁹ There is now strong evidence that for efficient coating, and for effective wrap-around, then powder has to be pneumatically projected onto the workpiece - or at least to within a few centimetres of its surface. The implications of this are important, and alter drastically the simplified scheme in Figure 1.10. Air flow patterns are as important, if not more important than the electric field configuration. Turbulence must be induced in order to achieve good wrap-around, and air velocities near the workpiece surface should not exceed the electrical image attraction force.

The original simple electrostatic model does not represent the original situation. Air flow has complicated the system and has probably contributed more than any other factor to the difficulties associated with system optimization. At the present time there are few guidelines to indicate optimum air flow in commercial systems, and system behaviour is usually approached empirically.

The secondary importance of electric field lines configuration is further demonstrated by the apparent effectiveness of tribo-guns for coating irregularly shaped workpieces. Wrap-around generally appears to occur just as effectively with tribo-charged guns where the deposition field is essentially eliminated. In practice, there will exist a small but finite electric field between the gun and workpiece, and this will be due primarily to the charged powder cloud itself. This is usually referred to as the space charge field. Elimination of the deposition field has unforeseen advantages, especially when the interior of cavities and corners are to be coated. For a convex geometry as depicted in Figure 1.10, the field lines may assist with particle movement and deposition on the surface. For a geometry similar to that shown in Figure 1.11, however, quite the opposite situation will occur. As a direct result of

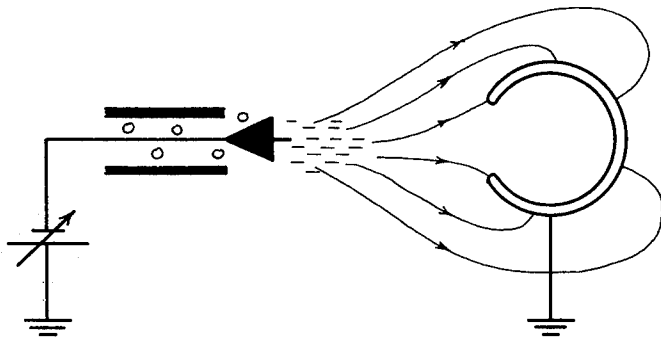


Fig. 1.11 The Faraday Cage effect.

Gauss' Law¹⁰, no field lines can exist, nor penetrate, areas that approximate to being surrounded by the earthed metal boundary of the workpiece. This has become known as the Faraday Cage effect, and is an illustration of one of the classical laws of electrostatics.

Most lines of electric field will terminate on the outside surface of the workpiece section shown in Figure 1.11. With low gun air velocity, particles will tend to follow more predictably the field line pattern, resulting in minimal penetration of the inside surface of the workpiece. This contrasts with a typical tribo-gun arrangement, where the electric field will be either zero or negligible, and particle trajectories will be dictated primarily by air flow. Pneumatic conveyance of the particles into the workpiece cavity will ensure internal coating and image charge attraction will complete the objective of depositing particles on the surface. Although the superiority of tribo-charged guns over corona-charged guns for internal coating is generally accepted, the explanation is relatively recent. Figure 1.12 illustrates typical coating behaviour expected with both corona and tribo-charged guns for workpieces with deep cavities.

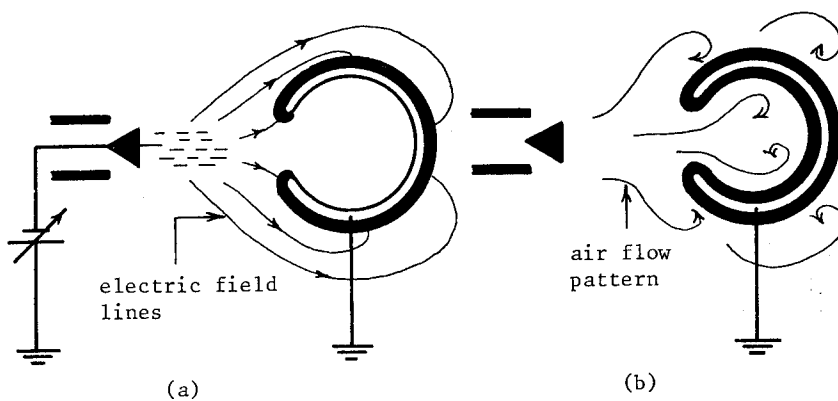


Fig.1.12 Typical coating patterns for (a) corona charged gun;
(b) tribo-charged gun.

This difference in coating ability between the two types of guns clearly illustrates the difficulties encountered in achieving acceptable coating performance on a commercial coater. For optimum coating efficiency and surface coverage, systems should be chosen to complement the geometry of the workpiece - an impossible situation, since the shape and size of workpieces often change on a day-to-day basis. In such cases, a compromise is inevitable, reflected by the fairly high proportion of commercial coating systems returning unbelievably low efficiency figures. This situation is being gradually improved by the introduction of novel gun designs (see Chapter 3).

BACK-IONIZATION

To achieve good-quality coating following deposition of charged powder particles on the workpiece, other factors must be considered. As the traditional model is no longer representative, the concept of

self-limiting of layer thickness requires some explanation. A simple model of layer thickness limiting is illustrated in Figure 1.13.

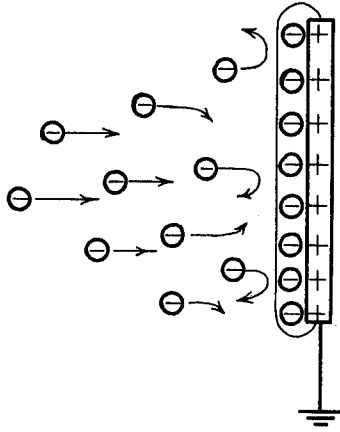


Fig. 1.13 Simple model of layer thickness limiting.

As the charged powder layer accumulates on the substrate, it might be assumed that at a certain value of surface charge density further particle accumulation will cease simply as a result of electrical repulsion. This model has been adopted for self-limiting.

Detailed investigations into layer behaviour have resulted in a modification of the model, and self-limiting is now recognised as being a direct result of back-ionization.¹¹ With a corona charged gun, Figure 1.14 more accurately represents the development of the powder layer than Figure 1.13. Both charged particles and a high density of free ions alight on the workpiece.

As the powder layer grows, the potential across its thickness increases with time as charged particles and ions accumulate. Since the particles, and hence the layer, are generally electrically insulating, the charge due to particles and ions will be retained. As coating continues, a layer potential is reached which exceeds the breakdown potential and spark breakdown will occur in or on the layer. Sparking usually occurs when the breakdown potential of air is exceeded (3 Mv.m^{-1}), because the coating is essentially a loosely packed matrix (see Figure 1.15). Bi-polar ions will be created by

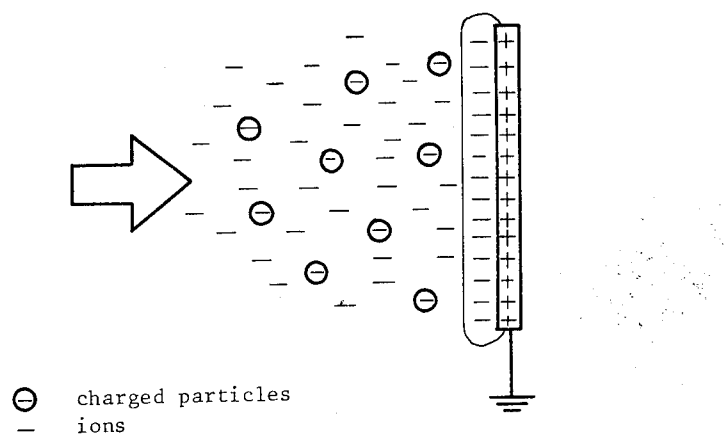


Fig. 1.14 Powder layer growth using corona-charged gun.

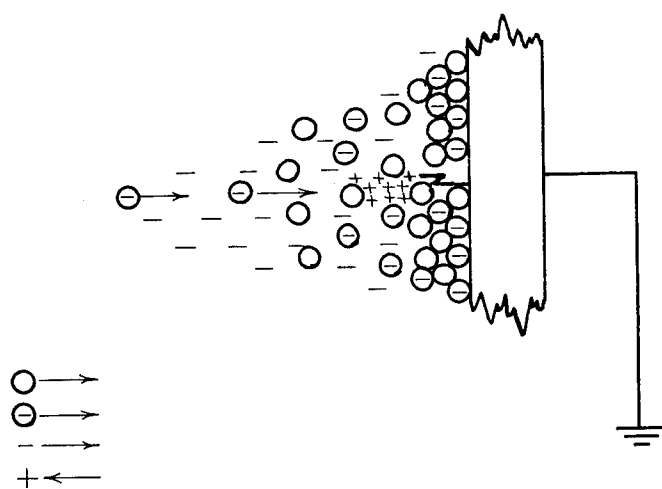


Fig. 1.15 Back-ionization in powder layer.

each discharge and the negative charge will be collected by the substrate, while the positive ions will drift away from the surface towards the gun, under the action of the externally applied electric field. This counter movement of positive ions immediately interacts with the oncoming negative ions and negatively charged particles resulting ultimately in neutralisation. Previously charged particles, after neutralisation, will no longer be able to contribute to the electrostatic deposition process, and thus coating ceases, corresponding to the familiar self-limiting of coating thickness, as a direct result of the onset of back-ionization. That is, the onset at back-ionization is associated with virtual cessation of charging of the gun. With most commercial corona-charged gun systems, back-ionization will commence once the first monolayer of powder has been deposited on the workpiece. Investigations have shown that generally back-ionization commences within about one second of trigger actuation, primarily due to the high free ion density with externally charged corona guns. Similar tests with tribo guns suggested a typical coating time of 10 ~ 20 seconds before the onset of back-ionization. Since no ions contribute to the potential build-up in the deposited layer, it takes much longer for the breakdown potential to be reached, relying entirely on the charge on the powder particles.

Figure 1.16 shows a typical example of back-ionization on an epoxy coated plate using external corona charging. The photograph was taken using an image intensifier, and illustrates clearly the severity of the mechanism. Analysis of slow motion pictures of the onset of back-ionization on a workpiece similar to Figure 1.16 indicated that discharges first appeared on sharp corners and edges, followed by fairly rapid spreading over flat surfaces. This would be expected, since initially points and edges would be preferentially coated due to geometrical field enhancement.

With subsequent build-up on the flat surfaces, back-ionization rapidly progresses over the entire workpiece.

Having established the mechanism responsible for self-limiting, the advantages of this unique characteristic can be assessed.

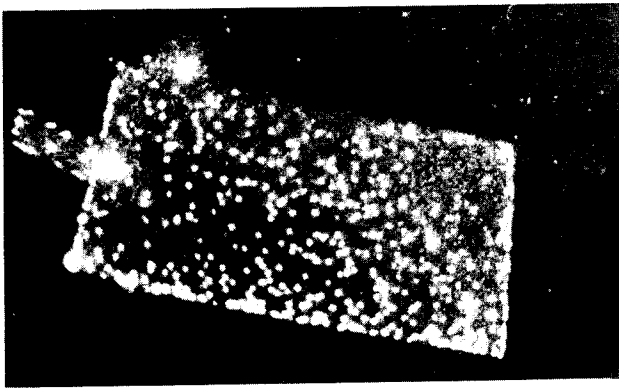


Fig. 1.16 Back-ionization on epoxy coated flat plate.

It is now accepted that self-limiting is a direct result of electrical breakdown of the deposited powder layer (cf. simplistic model in Figure 1.13); this in turn destroys the charging characteristics of the application equipment. Furthermore, the electrical discharging is associated with the release of substantial energy which leads to serious disruption of the deposited layer. It is this disruption which causes the familiar surface defect known as 'orange-peel'.

Another interesting characteristic of back-ionization, which may have important practical implications, is that surface disruption varies according to the polarity used on the charging gun.¹² Negative polarity, which has been chosen as the standard commercial configuration, is perhaps of greatest importance. The choice of negative polarity was primarily historical, because early high voltage generators were almost exclusively electrostatic revolving drum type machines. Negative primary charging was found to be more reliable and controllable, and for this reason almost all electrostatic generators were limited to negative polarity. However, the present availability of electronic voltage multiplier units ensures

that polarity offers no limitations to design and performance.

With negative gun charging polarity, the spark associated with back-ionization is a bulk phenomenon. That is, the spark channel actually penetrates the depth of the deposited layer and can create the familiar 'pin-holing', together with some degree of cratering which is associated with 'orange-peeling'. On the other hand, when positive corona charging is used, the nature of the back-ionization changes considerably. The discharge does not penetrate the deposited layer, but is more of a surface phenomenon. Using an image intensifier to view positive back-ionization reveals a continuous surface glow, rather than discrete point discharges associated with negative charging. There is no pin-holing, but the surface disruption usually tends to be more severe. Spark energy measurements on both negative and positive back-ionization indicates that negative sparks were generally more energetic than positive, which probably accounts for the ability of negative to penetrate the bulk of the layer.

Identification of important differences between positive and negative charging involved sophisticated experimentation. For example, the system illustrated in Figure 1.17 was used to distinguish between bulk and surface discharges.

A conducting transparent flat plate was coated on one side using a standard commercial corona charging gun. The mirrors facilitated simultaneous viewing of both the upper and lower powder layers, and visual recording of the discharges was made possible by the use of an image intensifier. Accurate matching of back-ionization sites was achieved by comparing the images appearing in mirror 1 and mirror 2. For negative charging, both images were matched indicating complete puncturing of the layer; whereas for positive charging, discharge sites appeared only in mirror 1 confirming the surface nature of the spark.

Spark energy values were measured using a relatively complex technique: an experimental workpiece which incorporated a small electrically isolated section, as shown in Figure 1.18. The diminutive size of this section facilitated the isolation of single layer discharges.

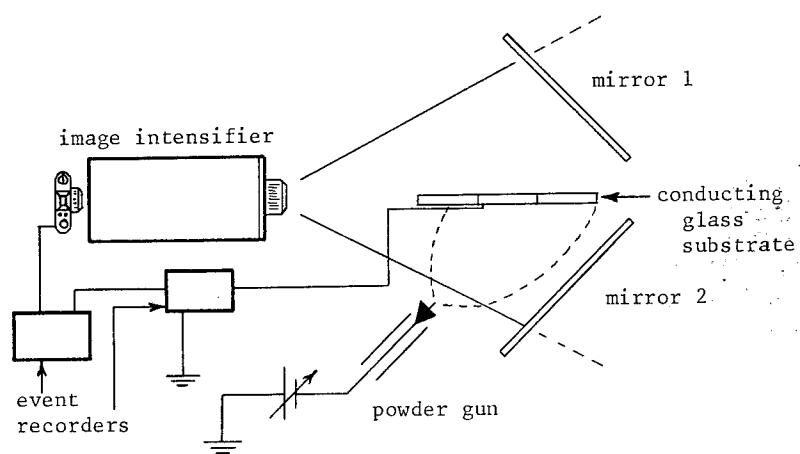


Fig. 1.17 Double image arrangement for back-ionization evaluation.

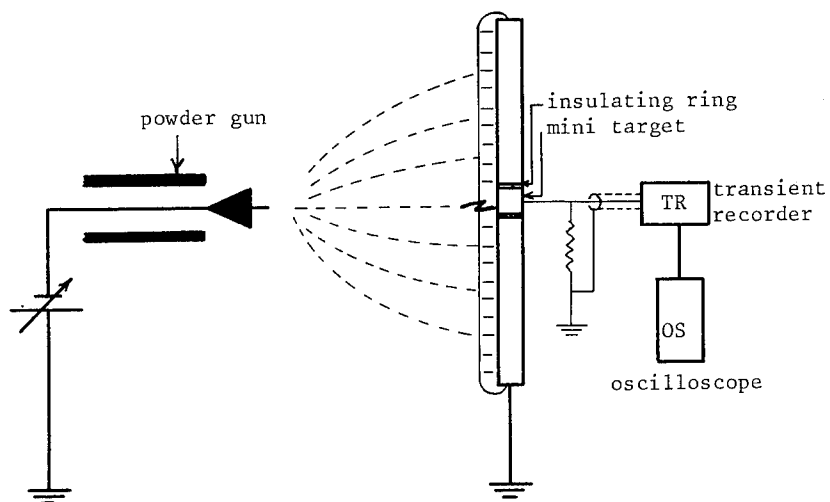


Fig. 1.18 Energy measurements of back-ionization.

In a system using a simple circuit and an oscilloscope, the appearance of a discharge on the test electrode triggered the oscilloscope and the energy associated with the charge transfer could be estimated.

These fundamental investigations suggested important practical implications.

For example, when the surface finish is of prime importance, that is the specification for the deposited powder layer is primarily aesthetic, negative powder charging may be the correct choice of polarity; orange peel will be minimised, but pin holes may exist. However, with the correct choice of powder offering adequate flow characteristics during curing, then most pin holes should be self-healing. On the other hand, if the coating appearance is of secondary importance and the prime objective is surface protection (automobile subframes and internal coating) then positive powder charging might prove beneficial. There may be widespread orange-peeling, but pin holing will be non-existent and paint flow characteristics become of secondary importance.

The choice of gun charging polarity may thus be more important than originally envisaged, both in terms of the type of coating required and, as was discussed earlier, in the type of powder used in different gun systems. For example, if a particular gun/powder combination were to show negative tribo-characteristics, then negative corona charging would be a logical choice of polarity; and conversely for positive. This aspect of charging behaviour is now well known, and some gun manufacturers now offer a choice of gun polarity.

It is generally accepted by experienced coaters that a tribo-charged gun deposits a far superior quality coating than a corona charged gun. Since no free ions are created by a tribo-gun, the charge build-up on the deposited layer is entirely due to the charged particles. Thus, the charge density in the layer is low and the layer breakdown potential will not be reached until a considerable thickness is achieved. Tribo-charged coating tests have indicated that layer breakdown or back-ionization may be initiated after about 10 seconds of coating time. The corresponding value for corona charging is about one second, or in most cases when the first monolayer of powder is

deposited.

Thus, with a tribo-charged gun, there is no back-ionization within the first 10 seconds; and consequently there is no disruption of the deposited layer which would lead to pin-holing and cratering. At the same time, there is no self-limiting and very thick layers are created; this is not a situation acceptable in most industrial coating applications. However, this may be compensated by careful control of conveyor speed and powder throughput.

Points of practical interest:

1. Corona-charged guns offer reasonably good control over powder charging.
2. Tribo-charged guns offer little control over powder charging and show erratic behaviour due to dependence on material and environment.
3. Tribo guns are good for coating inside cavities.
4. Free ions are detrimental to coating finish.

Best compromise for practical system:

Use corona charging for powder, but eliminate free ions emanating from gun head.

Powder application systems approaching this ideal requirement are now commercially available. These systems will be described later, together with a discussion of performance optimization.

CHAPTER 2

Measurement Techniques

Measurement of electrical parameters is, or should be, of paramount importance to equipment manufacturers, powder manufacturers and users. It is only by accurate measurement and careful interpretation of the results that any degree of system optimization can be achieved. Most of the measurements are straightforward, provided certain precautions are taken; while meaningful interpretation generally requires more skill. For diagnostic purposes and system evaluation, it is usually sufficient to measure just four electrical parameters. These are:

- (i) Powder resistivity ($\rho, \Omega m$)
- (ii) Powder charge-to-mass ratio ($q/m \text{ C.kg}^{-1}$)
- (iii) Gun potential (V. volts)
- (iv) Gun current (I. amperes)

Other parameters associated with complete system optimization and coating booth evaluation are:

- (i) Electric field ($E, \text{V.m}^{-1}$)
- (ii) Space potential (V. volts)

Knowledge of some or all these parameters will enable a fairly accurate assessment of the performance of a coating system, including identification of potential problems.

RESISTIVITY

In all applications requiring charging of particles, and subsequent manipulation of their trajectories, a knowledge of the particles'

resistivity is essential and critical with regard to system behaviour. A further complication is that for optimum coating behaviour in corona charged systems, there is apparently no ideal or optimum value of powder resistivity. In fact, any attempt at optimization necessitates a compromise in terms of resistivity as implied in the preceding chapter. At the gun head, the lowest possible resistivity is necessary to achieve efficient particle charging; once charging has been completed, the highest possible resistivity ensures that when the particle alights on the workpiece charge relaxation will be slow and good adhesive properties will be assured. Such a compromise situation exists in many electrophotographic image copying mechanisms, where the ink toner particles need to be as conducting as possible at the development stage (toner transfer onto latent image on the photo-conductor); but for the remainder of their duty cycle, should be as insulating as possible for good adhesion and transfer to the paper. Some toners achieve this compromise resistivity through a number of inspired innovations associated with formulation. Some toners display variable resistivity characteristics, with electrical properties changing according to pressure or electric field. To achieve this variability toner formulations are in general chemically complex and a similar approach is not thought to be feasible with powder paint. Currently the choice of material resistivity is limited. Most of the common materials such as epoxy, polyester, acrylic, nylon, polyethylene, etc. are inherently highly resistive (usually $> 10^{14} \Omega\text{m}$) and potentially display excellent adhesive properties. Efficient charging of such materials, however, is not straightforward (see Chapter 1). In terms of acceptable adhesion, then the lower limit of powder resistivity is approximately $10^{12} \Omega\text{m}$. Below this value, charging will be good but adhesion will be poor. Apart from adhesion problems with low resistivity powder, an important gain in coating finish will be achieved. Since charge relaxation will be rapid, the potential required across the coating thickness to initiate back-ionization will never be reached, hence no pin-holing or cratering will occur - even with high free ionic density. This should perhaps be considered in electrostatic systems using pre-heated workpieces,

where electrostatic adhesion is of secondary importance.

A number of methods have been developed for the measurement of powder resistivity. One of the simplest and perhaps most widely used methods is the bulk resistivity cell technique. A typical cell arrangement is illustrated schematically in Figure 2.1. The powder sample is poured into the cell and subjected to a steady d.c. potential (V), while the current (I) flowing in the external circuit is monitored.

The powder resistance (R) can be calculated from the Ohm's Law relationship:

$$R = \frac{V}{I}$$

Knowing cell electrode dimensions and spacing, the specific resistance, or resistivity, can be calculated using:

$$\text{Resistivity} = R \frac{a}{l} \Omega \cdot \text{m}$$

where a = electrode area (sq. m)

l = electrode spacing (m)

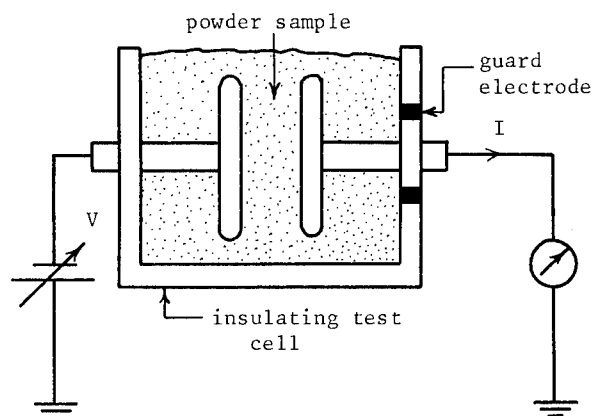


Fig. 2.1 Schematic of powder resistivity test cell.

This method is apparently simple but caution must be exercised, however, with respect to both the method adopted for data recording and the interpretation of the calculated parameter. For example, when a powder sample is poured into the cell, the possible effect of packing density on the conduction current must be considered. Should the powder be allowed to settle normally under gravity, or should a standard compression be applied to the sample surface? Numerous tests have been carried out on this type of test cell, and for the powder samples tested the application of pressure appeared to have a minimal effect on conduction. As long as the powder was allowed to settle normally into the test cell, by gently tapping its base on a bench top, then measurement of conduction current was reproducible. Of more interest, perhaps, is the actual construction of the test cell and the material chosen for its fabrication. The cell must itself be electrically insulating, but as many of the powder samples themselves are highly insulating ($> 10^{14} \Omega.m$), it is possible that the sample resistivity could exceed the cell resistivity. Under such conditions, when the current is monitored, and hence the resistivity calculated, the value obtained may well relate to the cell rather than the sample it contains. This problem could be largely overcome by incorporating a guard electrode into the cell wall, as illustrated in Figure 2.1. Any surface conduction component of current along either the inside or outside cell wall will be intercepted by the guard electrode and diverted to ground. The current (I) measured in the external circuit will therefore be entirely due to charge that has traversed the cell through the powder between the electrodes. Guard electrodes are essential if meaningful resistivity values are required, and careful cell preparation should precede all measurements. For example, both the inside and outside surfaces of the test cell should be thoroughly degreased in order to minimise surface conduction; and cells should be rigorously cleaned between sample loading.

When using this type of resistivity test cell, it is very common to observe a slow but steady decline in the current after application of the external voltage. This is especially noticeable when

conducting measurements on highly resistive powders. In some cases it can take up to 10 ~ 15 minutes before a steady current value is displayed. This effect is primarily due to polarization effects in the powder, with reorientation of dipoles occurring as a result of the application of a step voltage. As different species of dipoles re-orientate at different rates, the apparent initial high value of conductivity is extended over a period of time. When a steady conduction current is reached, then polarization will have been completely relaxed and the remaining current will be entirely due to charge conduction mechanisms in the powder sample itself. It is important, therefore, when performing resistivity measurements, to allow sufficient time for relaxation of the polarization mechanisms. Generally a 10 minute pause after the application of voltage is recommended before noting the value of the current.

More sophisticated powder resistivity meters are now available commercially, with direct readout of resistivity and autoranging facilities. The precautions mentioned previously apply to these types of instruments. With direct read-out of resistivity, then the initial reading will be low, gradually increasing to a steady value after the 10 minute relaxation period. A useful pre-check on these instruments is to note the resistivity of the empty cell. This should indicate either infinity, or the maximum range of the instrument. Any deterioration in cleanliness due to careless handling or inadequate laboratory techniques will be identified easily using the precheck; while reinforcing credibility in the accuracy of powder sample measurement.

Figure 2.2 illustrates a typical direct read-out powder resistivity meter. Considerable design improvements have been incorporated into this instrument; for example, the test cell itself bears little resemblance to the schematic shown in Figure 2.1.

To facilitate the cleaning of the test cell, the electrodes are an integral part of the cell wall, while still retaining the essential guard ring electrode. The electrodes are mounted in a horizontal plane, and the internal volume of the test cell reduced to a few

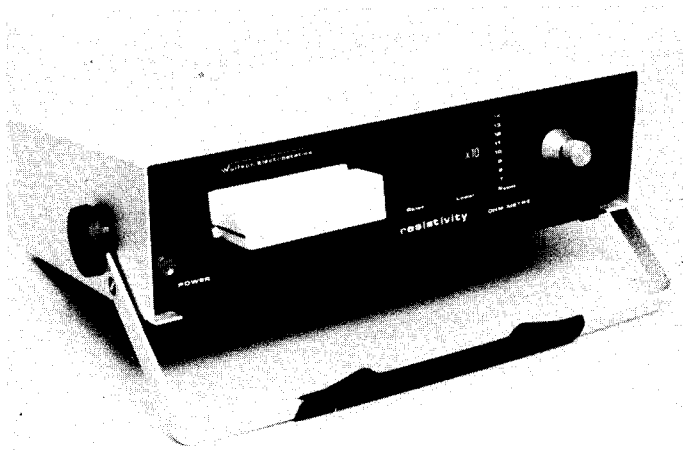


Fig. 2.2 Powder resistivity test meter.
(courtesy Wolfson Electrostatics Unit)

cubic centimetres. Easy cleaning is further enhanced by the unique 'splitting-cell' feature, which also greatly simplifies cell loading.

An alternative method of measuring powder resistivity adopts a non-contact charge decay measurement.¹³ This method is especially useful if only a small sample of powder is available, or if measurements have to be made on a sample already applied to a substrate. The method involves measurement of the electric field associated with an electrically charged layer of powder, as shown schematically in Figure 2.3.

Details of the field-measuring device, or field mill, will be discussed later.

The charge on the powder may be that due to the normal gun charging, or the powder may be deposited by some other means, and the layer later charged using a uni-polar corona source. At the end of charging,

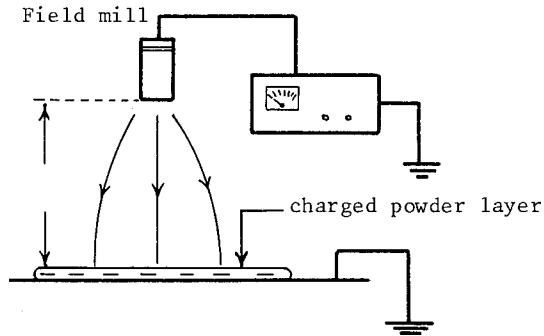


Fig. 2.3 Electric field measurement on charged powder layer.

the charge, and thus the electric field associated with it, will decay according to the relationship:

$$E = E_0 \exp \frac{t}{\epsilon_0 \epsilon_r \rho} \quad (4)$$

where ϵ_0 = permittivity of free space ($8.854 \times 10^{-12} \text{ F.m}^{-1}$).

ϵ_r = relative permittivity of powder.

ρ = volume resistivity of powder.

This exponential decay will have the general shape indicated in Figure 2.4.

The time constant, τ , from equation (4) will be given by:

$$\tau = \epsilon_0 \epsilon_r \rho \quad (5)$$

So measurement of τ from the decay curve, and knowing ϵ_r will allow calculation of ρ . If ϵ_r , the relative permittivity of the powder, is not known, then an additional measurement will be necessary. A capacitance measuring device, or bridge, will be required for this

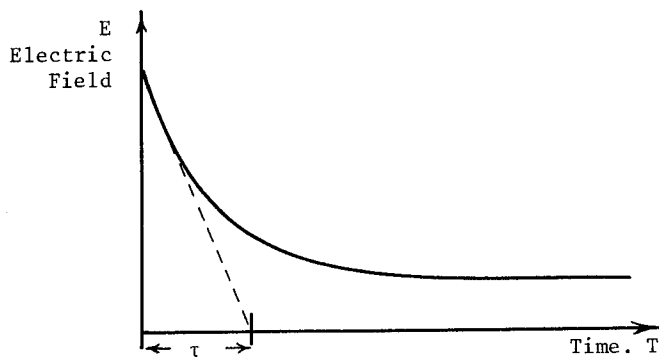


Fig. 2.4 A typical exponential decay plot of electric field versus time.

measurement which usually involves two measurements of capacitance.

An air filled capacitor is first measured on the bridge.

Let this be

$$C_o = \frac{A \epsilon_o}{d}$$

where A = capacitor plate area.

d = capacitor plate separation.

The air space between the capacitor plates is then filled with the sample powder, and a second value of capacitance measured using the bridge.

Let this be

$$C_r = \frac{A \epsilon_o \epsilon_r}{d} = \epsilon_r C_o .$$

Hence ϵ_r , the relative permittivity of the powder, will simply be:

$$\epsilon_r = \frac{C_r}{C_o} \quad (6)$$

So, from equation (5):

$$\text{Volume resistivity } \rho = \frac{\tau}{\epsilon_0 \epsilon_r} = \frac{\tau C_0}{\epsilon_0 C_r} \quad (7)$$

Thus, the value for volume resistivity is obtained by a more complex procedure than the direct read-out resistivity test cell.

INTERPRETATION

In the present discussion, the resistivity parameter for powder has been referred to as volume resistivity (S.I. units of $\Omega.m$). This may seem reasonable as it is assumed that, in the resistivity test cell, the charge conduction is actually through the bulk of powder sample. Likewise, using the charge decay model, it is assumed that charge conduction is through the bulk of the deposited layer towards the earthed substrate. This basic assumption justifies further discussion.

The powder sample in the test cell may appear as shown in Figure 2.5, when enlarged several hundred times.

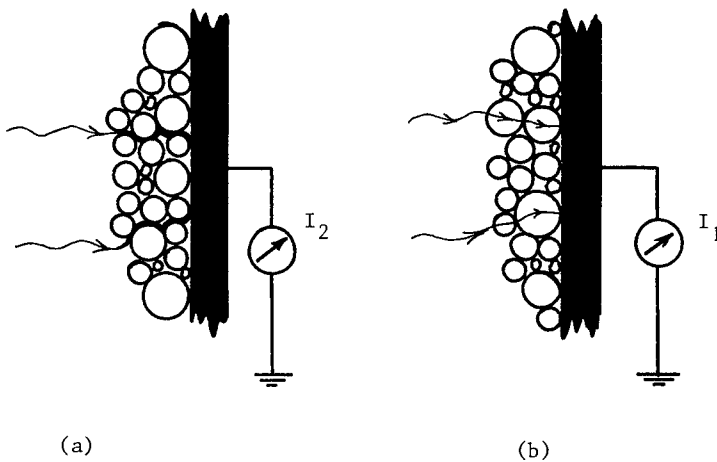


Fig. 2.5 Charge conduction paths in packed powder sample.
(a) Surface conduction; (b) Bulk conduction.

If the current, I_1 , measured in the external circuit is due to bulk conduction through the powder particles, the conduction paths might resemble those shown in Figure 2.5(b). However, if the powder is electrically insulating, it is difficult to imagine that the preferred path for charge migration will be through each powder particle. Under these conditions, a more realistic conduction path might be as depicted in Figure 2.5(a), where charge migration is essentially following the surface contours of each particle. In that case, the current measured in the external circuit, I_2 , will be representative of a surface rather than a bulk characteristic. For this reason, there will always be a certain degree of uncertainty in the interpretation of bulk resistivity of powders measured in this way, especially when the units of resistivity, ohm metres, are used to define what may be a surface effect. If conduction is a surface phenomenon, then the parameter will be resistance rather than resistivity, and the units will be ohms.

For highly insulating powders, this anomaly will always be present, and care should therefore be exercised when absolute values of bulk resistivity are required. For day-to-day comparative measurements, the resistivity test cells serve a useful purpose, provided the user is aware of the limitation.

The difference between bulk or volume resistivity, and surface resistance should perhaps be further clarified here. Resistivity, or specific resistance, was defined earlier.

The relationship $\rho = R \frac{a}{l}$ accommodates the bulk of the sample between the cell electrodes. If conduction is a surface phenomenon, then volume cannot be accommodated into the above relationship, and thus the often-quoted parameter, surface resistivity, cannot be meaningful. A standardised method of measuring surface conduction is illustrated schematically in Figure 2.6.

Two straight electrodes of length, l , are placed on the surface of the material under test, and spaced a distance, l , apart. With a voltage, V , applied to one electrode; a current, I , will be measured

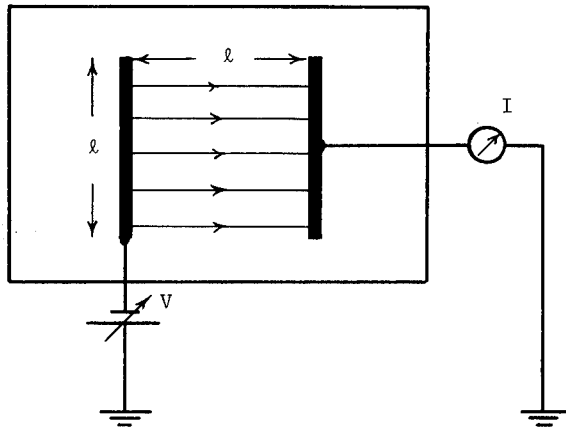


Fig. 2.6 Method for measuring surface resistance.

as shown. The surface conduction characteristic of the material will then be that of surface resistance in ohms. By using the square ($l \times l$) electrode configuration, normalisation of the parameter produces a new unit for surface conduction, that of ohms per square (Ω / \square). Thus, surface resistance differs from bulk resistivity; Table 1 emphasises the important difference between these two parameters.

TABLE 1. Surface and bulk conduction parameters.

| | Parameter | Units |
|---------------------------|----------------------------|--------------------|
| Surface conduction | Surface resistance | Ω / \square |
| Bulk or volume conduction | Bulk or volume resistivity | $\Omega \cdot m$ |

CHARGE-TO-MASS RATIO (q/m)

A measure of the ratio of particle charge to particle mass is a useful indication of how well the particle has been charged. There is a theoretical limit to the charge a particle can accommodate. (see the Pauthenier limit).

Measurement of q/m is very useful in practice as it immediately gives an indication of how well a particular gun system is working, which in turn may be used to assess the coating efficiency of a particular plant.

In its simplest embodiment, measurement of q/m is relatively easy to do; but as will be seen later, certain precautions have to be taken with most gun systems, and as with resistivity measurements the data obtained must be carefully interpreted. In order to measure the charge-to-mass ratio of a powder sample, two measurements are required. First, the charge on the powder, and secondly the mass of the powder sample. It is convenient to contain the powder sample in order to measure the mass, and for this reason the most suitable method of measuring charge is by means of a Faraday cup arrangement. A simple Faraday cup is illustrated in Figure 2.7.

As charged powder enters the cup, an equal and opposite charge flows from earth to electrically balance the charge residing in or on the cup. This charge will be measured on the electrometer, and will be equal to the total charge associated with the powder in the cup. The cup itself is usually accommodated inside another cup which is itself connected to earth. This outer cup, or screen, ensures that no induced charges are created on the measurement cup from some external source; that is, with screening, the induced charge on the inner cup will be that solely due to the charged powder entering it. If the openings on the face of the cup and screen are small compared to the overall area of the face, penetration of electric field

lines from an external source should be minimal. Following the measurement of charge, the inner cup may be removed from the screen, and the mass of collected powder measured. The total charge on the electrometer, divided by the total mass of powder in the cup, will then give the value of charge-to-mass ratio (q/m in Coulombs per kilogram. C/kg).

The difficulties associated with interpretation of this measurement arise when powder samples emanating from a corona charged gun are collected. Three species of particles travel between gun and work-piece (see Chapter 1): charged powder particles, uncharged powder particles and unattached free ions. If the Faraday cup arrangement is situated so as to intercept the powder flow from a gun, all three species will be collected by the cup. Since the free ion component of charge will normally be a few orders of magnitude in excess of the net particle charge, it is clear that the charge measured on the electrometer in the external circuit will be erroneously high and bear no resemblance to the true charge associated with the particles alone. Also, since both uncharged and charged particles will be collected by the cup, the mass of powder weighed at the end of the test will also be erroneously high and will not be representative of the mass associated with the charged particles. In order to rectify these measurement difficulties, certain modifications have to be incorporated into the simple Faraday cup arrangement illustrated in Figure 2.7.

Considering first the ionic component of charge, some method must be devised for capturing the free ions before they enter the inner Faraday cup. One approach adopts a metal screen mesh placed over the input port of the cup arrangement. With the correct choice of mesh size, it can be arranged that all the ions are captured by the mesh, while particles will be transmitted and collected by the Faraday cup. This separation of ions and particles relies primarily on the much higher mobility of the ions compared to the particles, with the momentum of the particles essentially conveying them through the mesh and into the cup. This ion/particle separation is illustrated schematically in Figure 2.8.

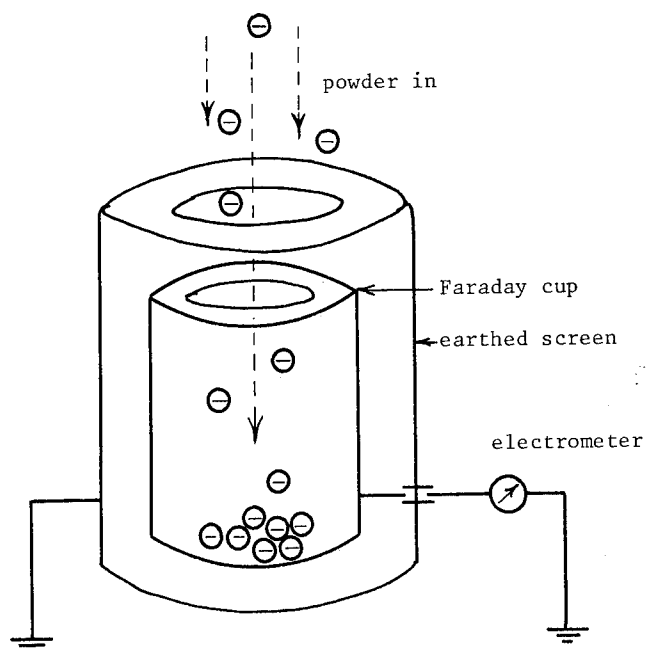


Fig. 2.7 Simple Faraday cup arrangement.

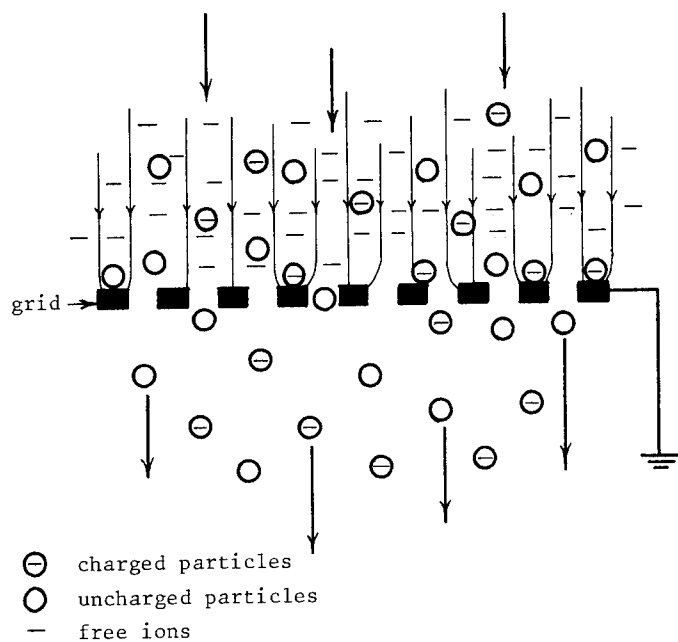


Fig. 2.8 Schematic of ion-trap in powder stream.

Although apparently satisfactory in theory, in practice the mesh itself rapidly becomes coated with powder and back-ionization will be initiated within about 1 second of the measurement. The result is that the charge on further oncoming powder is rapidly modified and the net charge measured on the electrometer will be erroneous and unrepresentative of the charging characteristics of the gun. The problem of uncharged powder particles entering the Faraday cup still persists.

For the mesh ion-trap to be effective, therefore, powder accumulation on the mesh itself must be avoided. A method in which this has been achieved very effectively involves incorporating an irrigated mesh arrangement to the charge-to-mass measuring device.¹⁴ This device also facilitates the separation of the charged and uncharged powder particles. A schematic of the arrangement is shown in Figure 2.9.

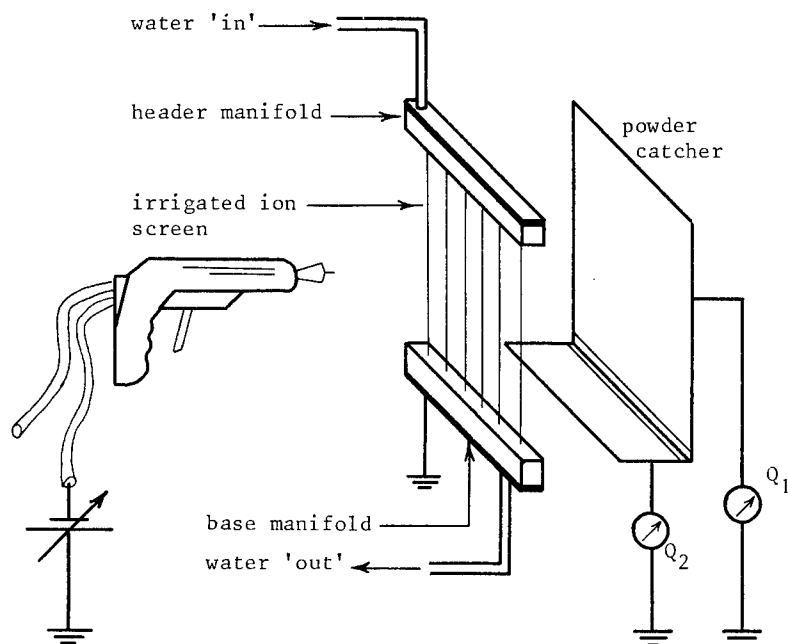


Fig. 2.9 Irrigated grid device for absolute measurement of q/m .

In one particular arrangement the grid wires were spaced approximately 10 mm apart. A manifold arrangement allowed the surface of all the vertical wire strands to be wetted and continually washed.

Behind the irrigated mesh, the familiar Faraday cup has been replaced by an L-shaped powder catcher. The vertical and horizontal sections may be electrically isolated and connected to earth via two separate electrometers, as shown in Figure 2.9; or they may be electrically connected and grounded through one electrometer. The implications of this arrangement will be explained later.

It is the continuous irrigation of the grid which prevents powder accumulation on the grid wires. Charged powder particles will still be attracted to, and impinge on, the wet earthed wires, but the downward motion of the water film prevents adhesion of the particle at the point of impact. Instead, the particles are flushed down into the base manifold where they are allowed to accumulate and the return water flow drains out of the system. All the ions are similarly trapped by the irrigated grid, and are immediately neutralised to earth.

At the irrigated grid, therefore, the first step in particle species separation has been achieved. The ions are removed without the creation of a secondary problem associated with grid back-ionization, and the charge measurement on the powder collecting plate will be that solely due to charge on the particles. In order to ensure the validity of this ion-capture technique, a number of comprehensive evaluations were necessary. For example, would the grid preferentially capture the most highly charged particles - thus effectively removing a 'cut' in the powder sample? Would the water disrupt off the surface of the wires when subjected to a high electric field? Careful evaluation under many different experimental conditions has indicated that such effects are minimal, and that the charge measured on the collecting plates is representative of the powder charging characteristics of the gun.

Having achieved separation of the ions without back-ionization, then the charged powder particles must be separated from the uncharged powder particles. This is not essential, and depends largely on the required characteristic of the gun. For example, if both charged and uncharged particles are collected and included in the q/m measurement, that will be a measure of the mean charge-to-mass ratio. If only the charged particles are collected and included in the measurement, a measure of the maximum charge-to-mass ratio

will be achieved. It is debatable which approach yields the most useful or meaningful result, and this, in turn, depends to a large extent on the objective of the test. For example, if data are required for the overall system performance, an indication of the mean q/m might be most important. On the other hand, using the L-shaped powder catcher enables a comparison to be made of the proportion of charged to uncharged powder, a useful measurement if gun charging efficiency is being evaluated.

This latter measurement is made possible by the split electrode facility as illustrated in Figure 2.9. Q_1 will be a measure of the charge associated only with particles that are sufficiently charged to ensure adhesion on the vertical face of the L-section electrode. Insufficiently charged, and uncharged, particles will alight and be collected on the horizontal face. The very low charge associated with this sample will be measured as Q_2 . Charge-to-mass ratio calculated from Q_1 and the vertical face only will be a measure of the maximum q/m . Charge-to-mass ratio calculated from $(Q_1 + Q_2)$ and the sum of the powder mass from the vertical and horizontal faces will be measure of the mean q/m . Finally, comparison of powder mass on the vertical and horizontal faces will give an indication of gun charging efficiency.

It would appear, therefore, that the irrigated grid method of measuring q/m is versatile both in terms of producing useful measurements and, for the first time, eliminating the detrimental effects of back-ionization. The measurement of absolute values of q/m is now possible for corona-charged guns.

This does not mean, however, that the more conventional grid-protected Faraday cup arrangement cannot be used; only that considerable care has to be exercised in its use and interpretation of results. A commercial version of this system is illustrated in Figure 2.10, where charge-to-mass ratio is just one function in a powder coating test set.

The precautions necessary when using this type of test cell include:

- (i) Awareness that the parameter measured will represent a mean

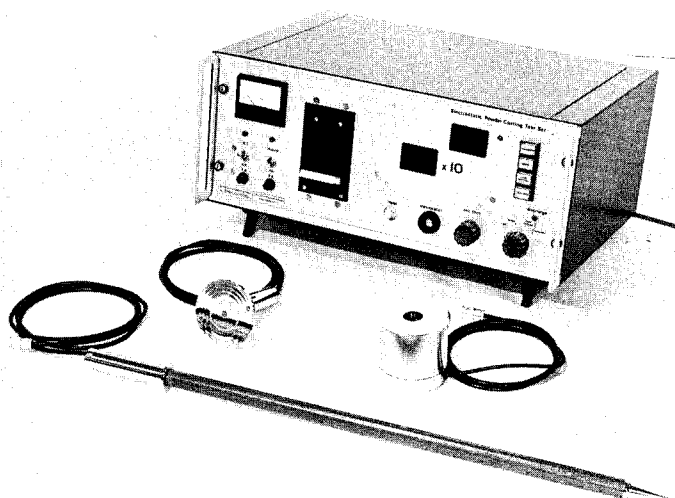


Fig. 2.10 Powder coating test-set.
(photo courtesy I.D.B., Ltd., Bangor)

charging characteristic of the powder gun.

- (ii) Powder collection times must be limited to about two seconds - or before onset of back-ionization on the ion grid. If necessary, several short bursts of powder collection may be made with the grid and cup lid cleaned of powder between each shot. Thus, sufficient powder will be collected for a reasonably accurate measurement of mass, and as long as the electrometer is not discharged, the charge collected per shot will be accumulative and only the final meter reading will need to be noted.

INTERPRETATION

In terms of gun and system evaluation, charge-to-mass ratio is as important as resistivity. This measure of the effectiveness of

powder charge, and the percentage of the total gun powder which is charged, gives a good indication of the expected performance of a gun system. In Chapter 1 an approximate value of the maximum q/m in a typical corona-charged gun is given as $10^{-3} \text{ C.kg}^{-1}$. In practice, this degree of charging results in exceptionally good particle adhesion, and a charge-to-mass ratio of $10^{-4} \text{ C.kg}^{-1}$ would be adequate. Generally, it is not difficult to achieve a high mean value of q/m , but what is more difficult and indeed considered more important, is to achieve a high charging efficiency. That is, what proportion of the total number of particles emanating from the gun are charged sufficiently to display adequate adhesion characteristics? The split L-shaped electrode in conjunction with the irrigated grid allows this important measurement to be made. This measurement should not be confused with the more straightforward charge-to-mass ratio.

GUN POTENTIAL AND CURRENT

The instrument illustrated in Figure 2.10 allows easy measurement of both gun voltage and current. In a corona-charged system, these are important parameters, which enable the operator to maintain either spot or continuous checks on the electrical supply to the gun. It should be stressed, however, that system behaviour cannot be assessed accurately from voltage (V) and current (I) alone. What may be considered as adequate gun voltage and current may not necessarily correspond to adequate gun performance. It is incorrect to assume that when a high gun voltage and current is indicated a high charging efficiency is guaranteed, leading to a high coating efficiency. In many instances, the reverse is true; the reason for this will be explained later.

Most commercial gun systems will have a voltage indicator located on the front panel of the control console. This voltage will be an indication of the output voltage of the high-voltage supply. Although commonly employed by equipment manufacturers, it is not the ideal method if voltage indication is to be used as a useful parameter in setting up a system for optimum performance. The important

voltage is the gun head voltage, i.e. that of the charging electrode itself; and this value could differ considerably from the output voltage of the high-voltage generator. In the extreme case, for example, there could be a break in the high voltage line between the gun head and voltage generator. The voltmeter on the control console would still indicate normal output voltage; however, the actual voltage at the gun head would be zero, resulting in complete loss of corona charging. An extreme situation, perhaps, but nevertheless one which could easily lead to a frustrating and time-consuming fault-finding exercise. A break of this type in the high-voltage line need not result in a drop or loss of indicated gun current, as the severed connection may well itself go into corona, albeit at a position remote from the gun nozzle and thus not contributing to powder charging.

A less extreme situation exists with this method of voltage indication under more normal gun operation. The high voltage leads on most commercial guns will incorporate a high resistance in series with its connection to the output of the high-voltage generator. This acts primarily as a current limiter and safety device in the event of the operator accidentally contacting the charging electrode while the gun is operational, or that the gun head sparks over to an earthed object, thus creating a potentially incendive situation. With such a resistive load, and with current flowing through the gun charging circuit, there will be a substantial voltage drop between the output of the generator and gun head. In that case, the voltage indicated on the control console will be quite different to the voltage at the charging electrode.

For example, consider a typical commercial gun system with a resistive load of 500 M Ω in the high voltage cable. Assume the output voltage of the high voltage generator indicates 70 kV, and that the gun current was 30×10^{-6} Amps. This would represent a voltage drop of about 15 kV along the length of the cable, with the resulting voltage at the head of the gun therefore being 55 kV and not 70 kV as indicated. The implications of this voltage drop may not be

important when operating at indicated output voltages in excess of about 70 kV. However, if a coater requires to be finely tuned and operated at what may approach a lower threshold voltage, then it is important to compensate for this voltage drop between the output of the high-voltage generator and gun head. In practice, this can be neglected and the indicated voltage assumed to be the gun voltage.

In practice, it is often more satisfactory, therefore, to measure the voltage appearing at the gun head; this may be performed quite easily with a voltage probe similar to that illustrated in Figure 2.11. This voltage measurement technique is one of the functions incorporated into this particular instrument. The measurement itself relies primarily on indicating the voltage dropped across a high resistor, which is incorporated into the body of the probe. Typically, for a probe resistance of $1000\text{ M}\Omega$, a current of $1\text{ }\mu\text{A}$ flowing through it will represent a voltage of 1 kV . The simple circuit is illustrated in Figure 2.11.

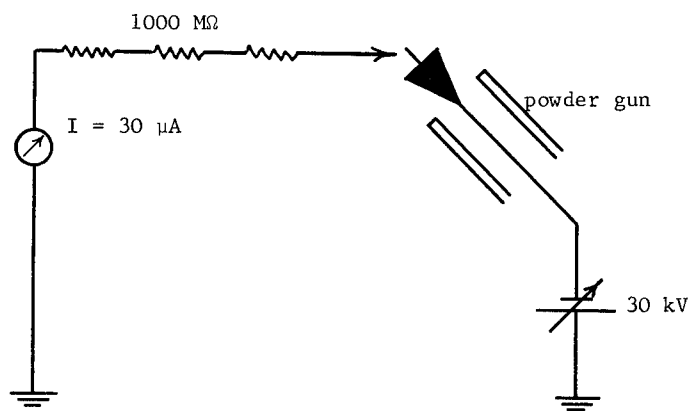


Fig. 2.11 Schematic of resistor chain voltage probe.

This is just a convenient choice of resistance, so that $1\text{ }\mu\text{A}$ represents 1 kV .

The weakness of this method is that the measurement itself relies

on current flowing through the resistor chain; that is, the measurement loads the high-voltage generator connected to the gun, and may interfere with the current capability of the device. So, in a situation where the gun may be operating at or near the current limit of the generator, the use of this type of probe will change the overall gun charging characteristics. A more satisfactory method for measuring voltage is to use a non-interfering voltage probe, and a number of commercial instruments are available which offer this capability. One type is shown in Figure 2.12. Here the upper electrode is connected directly to the high voltage to be measured. Due to its geometry, it will not support a corona discharge, and the only current corresponds to the charge transferring to the measuring sphere. Once the sphere has attained the potential of the gun electrode, no further current will flow. The actual potential is calculated from a measure of the electric field associated with the charge on this upper electrode. The electric field is measured by means of a field mill (see later in this chapter) incorporated into the lower electrode of the measuring voltmeter.

Although slightly cumbersome, and perhaps not quite as accurate as the resistor chain method for measuring voltage, this instrument does nevertheless offer the advantage of zero current drain - an important consideration when measuring voltages on current limited circuits. Both the probe and field techniques are polarity sensitive.

INTERPRETATION:

In powder application equipment, a knowledge of both charging current and voltage is essential if any degree of system optimization is sought. Contrary to general belief, the current is a more important and crucial parameter for optimum performance. Without sufficient charge being created at the gun head, particle charging efficiency will be correspondingly low. As was discussed earlier (Chapter 1), efficient ionic attachment to individual particles is not easy to achieve, hence the requirement to generate a disproportionately high charge density ion cloud in order to achieve, at best, a charging efficiency of about 60%. The penalties of creating such a



Fig. 2.12 Electrostatic voltmeter.
(Courtesy I.D.B., Ltd.)

high free ion cloud have already been discussed with regard to onset of back-ionization and its implications. In most conventional pistol applicators, a relatively high voltage is required to generate this high charge density ion cloud. This arises primarily from the fact that the entire gun voltage is dropped between the gun head and work-piece - a distance which typically may be about 1 metre. To achieve a sufficiently high intensified field for corona onset at the charging electrode, therefore, a correspondingly high voltage is required.

If E = Electric field ($V\ m^{-1}$)

V = Voltage (V)

d = Gun/workpiece spacing (m)

Then

$$E = \frac{V}{d}$$

So with large d , V must also be large to achieve large E .

The high voltage was originally thought to be important, not just for the creation of the corona discharge, but also to realise the familiar electrostatic coating model of particles following electric field lines; this has since been disproved. Air flow appears to dominate in terms of conveying particles to close proximity of an earthed workpiece, and some tests have clearly indicated that a more even wrap-around is achieved with the workpiece actually in a field-free region.¹⁵ So, in some respects a high voltage on an externally charged corona gun is not necessarily conducive to good performance.

Consider the implications of high gun voltage:

TABLE 2. Effects of higher gun voltage.
(Externally charged corona).

| | Advantages | Disadvantages |
|--|---|---|
| Higher gun voltage, leading to higher gun current. | Possibly increases charging efficiency at gun head. | Enhanced back-ionization. Wrap-around deteriorates. Poor penetration. |

Table 2 clearly shows that the disadvantages far outweigh the advantages of increasing gun current by means of a higher gun voltage. Both wrap-around and penetration suffer as a direct result of particles attempting to follow lines of electric field. That is, there will be preferential coating initially on areas of the workpiece with the smaller radius of curvature, while no field lines will penetrate corners and cavities resulting in poor penetration.

It would appear, therefore, that in this type of externally charged corona application equipment, a further compromise must be sought for optimum performance. In addition to a compromise choice of powder resistivity, the voltage/current combination must also be carefully chosen. The voltage must be sufficiently high for the creation of a corona discharge, but not so high as to adversely affect the particle trajectories between gun and workpiece.

It is difficult, and indeed impossible, to quote definite values for optimum voltages and currents. The performance of each individual system will depend on so many variables; these include:

- The type of gun used.
- Powder. Particle size distribution.
- Powder resistivity.
- Shape of workpiece.
- Distance between gun and workpiece.
- Current capability of gun high-voltage generator.

However, a general guide to improved operating procedure might include the following points on a simple check-list:

1. Without powder flowing through the gun, check gun current for various gun voltages.
2. Observe drop in gun current with powder flowing through gun.
3. Observe variation in gun voltage and current with spacing between gun and workpiece.
4. Note difference in deposition characteristics with different shaped workpieces.

In order to gain any benefit from the above setting-up procedure, measurement of charge-to-mass ratio will be necessary as discussed earlier. A charge-to-mass ratio of at least 10^{-4} C.kg⁻¹ must be achieved if acceptable coating behaviour is expected. The combined effects of gun voltage and current will be found to be crucial, especially for complex-shaped workpieces that have many sharp corners, edges and points, and deep cavities. Rounded geometries and smooth

surfaces will accommodate a much wider range of gun voltage/current before deterioration of the coating performance and quality becomes evident. The more complex the geometry of the workpiece, therefore, the more difficult it will be to arrive at a compromise operating set-up.

Under normal operating conditions, there would appear to be a great temptation to increase both gun voltage and powder feed rate in an attempt to improve particle deposition; this would have quite the opposite effect. Increasing gun voltage will generally increase gun current which will in turn enhance back-ionization, leading to a deterioration in deposition. Likewise, increasing powder feed rate will decrease gun current, resulting in an overall decrease in charging efficiency.

Some measurements, combined with observation of coating behaviour, should ensure acceptable performance. First, measure q/m , gun current and voltage, then proceed with visual assessment. At least the initial measurements will identify a starting point from which 'fine tuning' of the system may be performed subsequently in order to achieve optimum performance.

ELECTRIC FIELD

It is often desirable to have some knowledge of the value of the electric field that exists within a coating booth, especially at regions near the booth walls, as this will be one of the high field regions and be responsible for conditions most likely to detract from good system performance.

Measurement of electric field is reasonably straightforward, and a variety of commercial equipment is readily available. One of the most common, and perhaps most robust, instruments is the field mill. One type of field mill is illustrated in Figure 2.13.

In its simplest form, this type of instrument basically measures the voltage due to induced charge on a sensor electrode. Usually two sets of sensors are incorporated into the measuring head, with a rotating vane electrode arranged so that the static sensors are

alternately screened from and exposed to the region of charge to be measured. In this way, a square wave is produced which is subsequently amplified and processed in such a way as to give an output signal representative of the electric field at the sensor head. Most instruments of this type are polarity sensitive, and are available with a varying degree of sophistication. For example, a hand-held version of the instrument is usually quite adequate for rough assessment of electric field, while a more precise instrument similar to that shown in Figure 2.13 would be required for accurate data recording. Specialised instruments allow field measurements to be made in adverse environments; for example, in a dusty or wet environment, or in a location which may be potentially incendive.

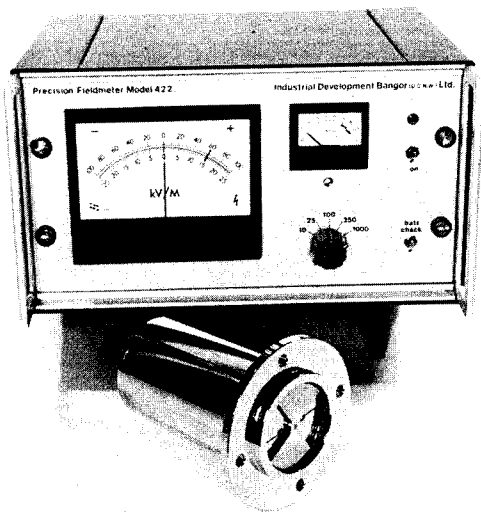


Fig. 2.13 Rotating vane type field mill.
(Courtesy I.D.B. Ltd.)

Other types of field measuring instruments include a vibrating reed sensing head, and a radio-active detector. The measurement of electric field is probably the best served of all electrical parameters in terms of the availability and variety of commercial instruments.

INTERPRETATION:

As with all measurements, some care must be exercised both in the execution of the measurement itself and in its interpretation.

In many powder coating applications, it is necessary to measure electric field in what is invariably a very dusty environment. The correct choice of instrument is therefore crucial. If the instrument is to be used in a powder coating booth, for example, then the first consideration must be the safety aspect, and the instrument should be certified as safe for use in an incendive environment. Since most sensing heads are fabricated of metal and are normally earthed, insertion into a powder booth will result in rapid coating of the head including the rotating vane sensor. This invariably leads to erroneous readings, with eventual seizing up of the vane drive motor. Under such conditions, therefore, it is essential to ensure that the sensing head is continuously purged thus preventing particulate collection. Some commercial field mills are offered with purging facilities as standard equipment. Others may have to be modified according to requirements. A simple method of achieving quite efficient head cleaning is illustrated in Figure 2.14. This is a well tried technique for use in powder storage silos¹⁶, and has been used successfully over an extended period in large silos.

The small air jets directed onto the surface of the sensing head ensure that no particles alight on the vanes.

As with all field mill measurements, caution must be exercised in locating the sensing head in order to record a meaningful value of electric field. Typical of most electrical measurements, the existence of the instruments affects and modifies the environment in which the measurement is being made. This problem is very evident when using the field mill. Imagine, for example, using the field-

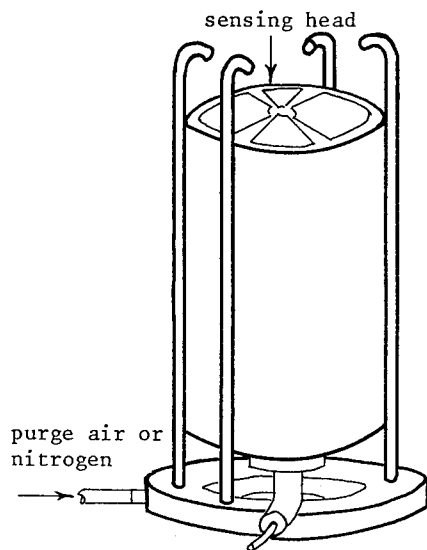


Fig. 2.14 Modified field mill head with air purge facilities.

mill to measure the electric field associated with a charged particle cloud in a silo. Normally, the field-mill head may be lowered into the silo, in close proximity to the charged cloud. Since the head itself is normally earthed, the lines of electric field may terminate as depicted in Figure 2.15.

That is, there will be an artificially enhanced electric field in the vicinity of the field mill; and it is this intensified field which will be recorded on the instrument. As long as this intensification is appreciated and compensated for, then use of the field mill in this way is quite acceptable. With purging jets located on the head, as shown in Figure 2.14, then intensification will be further enhanced and the value of electric field recorded will be further modified. The purging air will itself introduce a further modification which should also be compensated for. This arises as a result

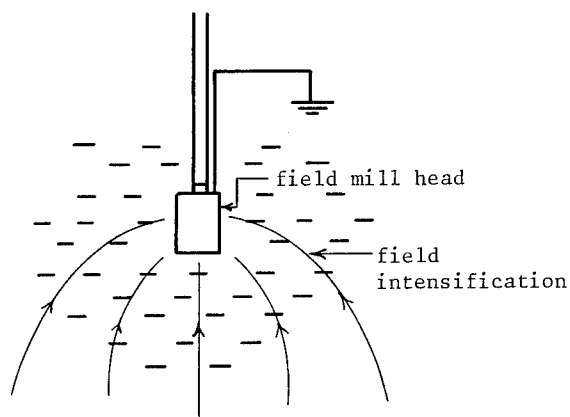


Fig. 2.15 Field intensification due to presence of field mill in charged cloud.

of the air blast disrupting the charged powder cloud in close proximity to the measuring head. Special care should therefore be exercised when purging is used.

A better way of using the field mill to measure electric field is to ensure that, whenever possible, the plane of the segmented electrode is parallel with and surrounded by a large flat guard electrode. This may be achieved relatively easily in a silo by installing the head flush with a side wall - the silo wall itself acting as a guard electrode. The electric field thus measured will be a true unintensified value of the field at the silo wall. If purging is limited to low air velocities, this measurement may approach an absolute value for electric field.

In hand-held field mills, this guarding or shielding of the head will be more difficult to achieve. However, some instruments are supplied with a small screw-on shield which certainly helps with reducing the error due to field intensification.

For powder coating applications, field mills or field detectors are useful instruments for rapid assessment of coating system behaviour,

for example one application is illustrated in Figure 2.3, where a field mill is used to measure the resistivity of a deposited layer of powder. Charge build-up on the booth walls may be assessed easily, and some indication of gun charging behaviour may be achieved simply by noting the field associated with the powder cloud emanating from the gun nozzle. This latter measurement is easier to interpret when used with tribo or egd-type guns, otherwise the field measurement will include the contribution due to free ions and the field due to the high voltage electrode itself. One type of on-line earthing tester uses a field mill to detect voltage build-up on poorly earthed workpieces¹⁷, a useful indication and monitor of the deterioration of the effective workpiece earthing through the jigging hook.

CHAPTER 3

Application Equipment and Booths

The charging and application of powder particles to an earthed substrate may be achieved in a number of ways. Perhaps the most common method of application is the gun or pistol applicator. In its simplest embodiment, this is no more than a hollow tube or pipe through which powder is conveyed in an air stream from a hopper. At the gun nozzle, the powder is usually charged and dispersed into a cloud. For small workpieces, fluidised bed coaters appear to have certain advantages; where the workpiece, powder and charging electrodes are retained within a relatively small enclosure. Between these two extremes lies a variety of hybrid systems, each one offering its own unique advantage for special coating requirements.

PISTOL APPLICATORS

In terms of choice of hardware, pistol applicators probably offer the greatest variety and often present the 'would-be' coater with a difficult choice in terms of suitability and optimized performance. However, all pistols generally share the same basic construction - powder emanating from a hollow tube; variations might include hand-held or automatic reciprocating models. The number, positioning and mode of operation of the corona charging electrodes will differ widely for different manufacturers. Air flow control nozzle and diffuser arrangements will vary, and powder charging methods will either be corona or tribo, or a combination of the two.

For a particular coating application, it is not always easy to choose the most suitable system, and indeed choice is often dictated

by performance assessment on demonstration equipment. Factors to be considered, in addition to apparent good coating performance, will be discussed later. However, a useful starting point might be a consideration of the types of pistols available.

The most common type will incorporate a single short pointed electrode at the gun nozzle. Usually, this single point electrode will be located, and protrude from, the centre of the powder diffuser. The electrode is normally fixed in position, the only degree of adjustment offered being the potential applied to it. It is surprising to find that the majority of corona-charged guns differ little from this basic arrangement, i.e. similar to that adopted for some of the first commercial guns ever produced. As explained earlier, this arrangement has proved to be reasonably effective in terms of particle charging, although an excessive population of free ions must of necessity be produced. The implications of this on coating performance and quality have already been explained in detail. It is surprising to find that many currently-produced pistols offer little or no adjustment of the corona charging electrode. Generally, one fixed electrode is expected to cope with an infinite variety of coating situations. For different workpieces, powder, conveyor speed and powder feed rate, only electrode voltage and current are offered as system variables from which optimization of charging efficiency is expected. Some manufacturers now also offer a choice of charging polarity, as this can have a significant effect on the charging efficiency of powders that display high tribo-charging characteristics.

One of the important points of consideration during equipment demonstrations and evaluation is indicated by the previous discussion. That is, always check the gun coating behaviour with the charging voltage switched off. If possible, and if equipment is available, a measure of the powder charge-to-mass ratio (q/m) and polarity would also be a most valuable indicator. For example, if the natural charging tendency of the particular powder under test was 'positive', then 'positive' corona charging should be chosen for the gun, and

negative for negative charging tendencies. For some materials, such as nylon, tribo-charging levels can be comparable to, and sometimes exceed, the corona charging contribution. In such cases, this test will be especially important if system optimization is to be achieved. The problem, of course, with polarity choice is that equipment is often expected to cope with a variety of powders, in which case a fixed polarity high voltage supply may not be ideal. The tribo-charging component in pistol applicators either originates from the gun barrel itself, or the powder feed line between hopper and gun, or a combination of both factors. Care should be exercised, therefore, when choosing a particular gun nozzle material specifically for tribo-charging qualities, as this may be drastically modified if at a later date the powder feed line is exchanged or renewed with possibly a pipe of different material.

This natural tendency for powder particles to become charged by friction is used as the prime charging source in some commercial guns.¹⁸ For a known combination of gun material and powder, this approach offers a number of advantages over corona charging. The high-voltage supply may be eliminated, which offers a considerable cost saving; but this may not in itself be the most important gain. Since no free ions are created, the coating time may be extended before the charge density within the deposited layer will have accumulated sufficiently to cause back ionization. For most coating arrangements, the coating time will be well below the back ionization onset time, thus ensuring that the coating quality with tribo-charged guns is generally of very high standard. Also, since no high voltage appears at the gun nozzle, the electric field between gun and work-piece is low and due only to the charged particle cloud. This enables easier access of charged particles into cavities and recesses, the particle trajectories being dictated more by the air flow pattern than by the electric field.

These are all clear advantages over conventional corona-charged gun systems. For a fixed combination of gun and powder, tribo guns would appear to be the ideal choice. Long-term charging efficiency should,

however, be thoroughly evaluated. For some materials, there is a tendency for powder to partially cure and adhere to the internal charging surfaces of the gun. This 'filming' affect can have disastrous consequences on overall charging behaviour, and may not be immediately evident in a new system, or a system running over a short period of time. It is suggested, therefore, that tribo-gun evaluation should extend to at least a five-hour continuous running programme if a realistic behaviour pattern is to be achieved.

Another problem common to most pistol applicators is to ensure continuous, reproducible and controllable powder flow from the hopper to the gun itself. A variety of hopper and feed systems are available, but few offer accurate metering of the powder. In addition to the electrostatic characteristics of different guns, powder metering must rank as one of the most important design criteria in coating systems. Generally, problems arise during switched gun operation, whereby during switch-on powder delivery tends to commence with a high particle density cloud. The primary cause of this is residual powder deposited within the feed pipe and gun nozzle following switch-off. Even for continuous gun operation, a constant and accurate powder feed rate is difficult to achieve. This is especially important when a low volume of powder is delivered to the gun. These two problems related to powder handling must be areas where further fundamental design optimization would contribute greatly to an improvement in pistol applicator performance.

FLUIDISED BEDS

The projecting of particles through a nozzle is not always the best and indeed the most convenient approach to depositing an even coating on a substrate. For many applications, a fluidised bed technique may offer considerable advantages.

In its simplest embodiment, this system comprises an enclosure within which the powder will be confined. By a combination of air flow and mechanical vibration, the powder may be fluidised and simultaneously be electrically charged. Charging is usually effected by means of high voltage electrodes situated at or near the base of

the container. The electrodes may be sharp points, or more usually small diameter wires. The application of high voltage to these electrodes results in the creation of a high charge density ion cloud by virtue of corona ionization. A schematic of a simple fluidised bed coater is illustrated in Figure 3.1.

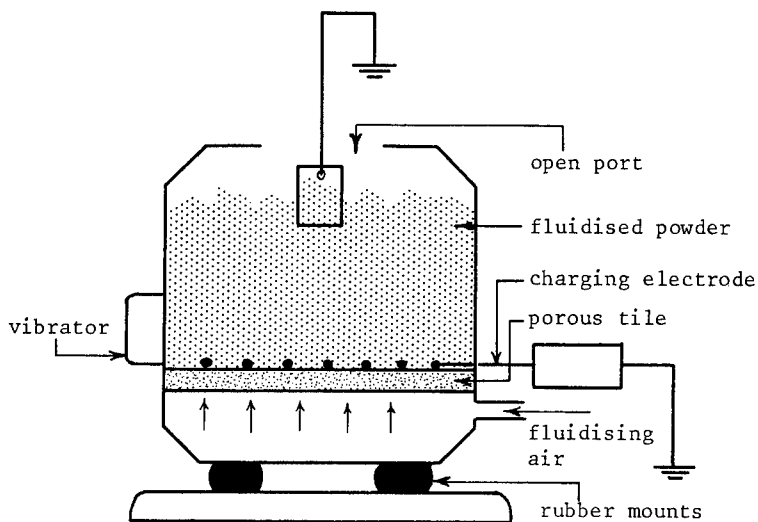


Fig. 3.1 Schematic of simple fluidised bed coater.

Normally at the top of the coater enclosure, an open port allows escape of the fluidising air, while at the same time offers access into the enclosure of small workpieces.

In many ways, this approach is very attractive especially for relatively small workpieces. The powder is confined to an enclosure and is therefore much easier to handle, since there is no requirement for collecting, recycling and re-blending overspray. In fact, the overspray is continually recycled and re-charged within the confines of the coater box. Unlike pistol/booth arrangements, where each particle effectively has only one chance of being charged - when

passing through the gun nozzle; in a fluidised bed, particles are continuously recycled and therefore permitting multiple charging/deposition cycles. Due to the absence of reclaiming and re-blending equipment, fluidised beds are generally very compact compared to pistol/booth combinations.

A typical configuration for coating is illustrated in Figure 3.1, where an aperture near the top of the booth allows the workpieces to be either inserted into the powder cloud or passed over the opening on a conveyor belt. Some units have ports in the booth wall, thus allowing a conveyor and workpieces to pass right through the charged powder cloud. In such cases, a slotted dividing wall between the conveyor and workpieces ensures that the conveyor itself remains powder free. Figure 3.2 illustrates a typical commercial fluidised bed coater for small workpieces. This particular configuration offers the interesting feature of rapid colour change. Powders of different colours are contained in separate removable cartridges which may be easily inserted into the coater unit.

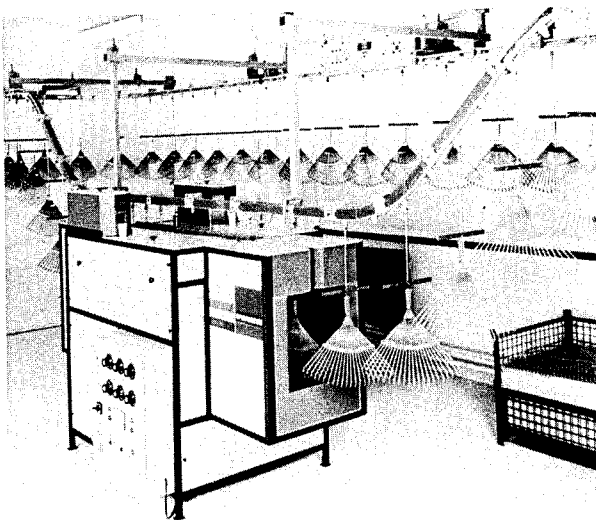


Fig. 3.2 Typical commercial fluidised bed system.
(photo courtesy Brennenstuhl)

Although totally enclosed fluidised bed systems offer numerous operational advantages, some care must be exercised in the choice of equipment and the mode of operation; for example, if workpieces are inserted into the coating box, the possibility of electrical sparking between an earthed workpiece and the high-voltage charging wires may lead to ignition of the fluidised powder. This might occur, for example, if the workpiece becomes too close to the charging electrodes, or for some reason a workpiece falls off the conveyor onto the electrodes. Special care should be exercised if workpieces are dipped into a fluidised bed, as this is when contact with the charging electrodes is most likely.

This particular hazard may be eliminated to a large extent by using rather special powder charging techniques. Some commercial units now incorporate inherently safe charging systems.¹⁹ One type is illustrated schematically in Figure 3.3. Here, the high voltage charging electrodes are retracted below the porous air tile. In this way, no bare high voltage electrodes exist within the powder enclosure itself, and indeed a bare hand may be inserted into the box and placed on the surface of the porous tile even when operational. This system relies on transmission of the air ions through the porous tile, with attachment to paint particles then being effected in what is essentially a totally separate enclosure to that in which the high voltage electrodes are housed. No doubt some loss of ions occurs to the porous tile, but this does not appear to impair the overall performance of this system. In addition to this inherent safety feature, the coating performance will be different compared to conventional charging electrodes, since the deposition field will be substantially modified. In the inherently safe system, it is envisaged that particle trajectories are dictated primarily by the air flow pattern and the field due to the charged powder cloud itself (the diffusion field). With exposed charging electrodes, the field between the high voltage electrodes and workpiece would be expected to affect trajectories, especially in relation to access of charged particles into corners, cavities and other electrically screened areas (see Chapter 1, with reference to the Faraday cage

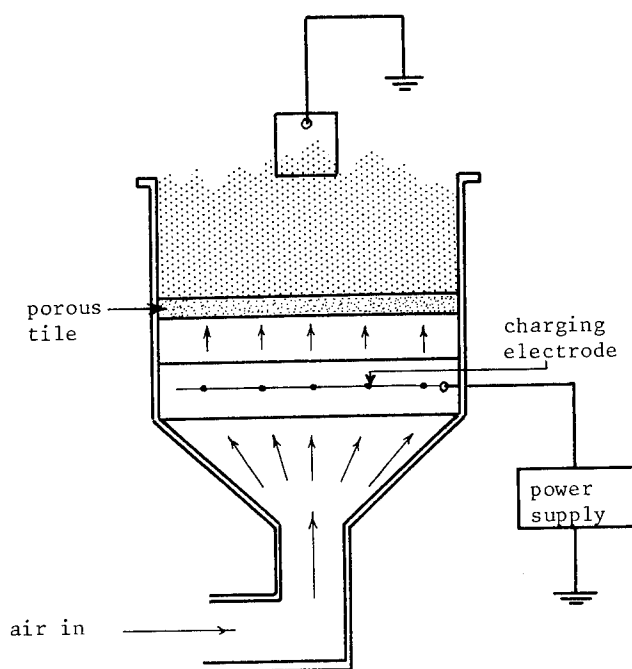


Fig. 3.3 Inherently safe fluidised bed.

effect). In this respect, superior particle penetration would be expected with a system similar to that illustrated in Figure 3.3. Coating behaviour and quality will obviously be dictated by many other parameters and conditions such as size of the workpiece relative to the powder enclosure, the electrical characteristics of the powder enclosure, air flow patterns and type of powder used.

Another common problem, not immediately obvious but nevertheless worthy of careful appraisal, arises when powder of wide particle distribution is used. Separation, or stratification, of particles may occur, resulting in the larger particles occupying the lower levels within the fluidised bed, with the fines being elevated to

the upper levels. If a relatively large workpiece is inserted into the fluidised bed, then both coating quality and thickness may vary over its surface. Likewise, small workpieces repeatedly inserted to approximately the same depth will result in a gradual change in overall particle size distribution leading eventually to variable booth performance.

These two problems unique to fluidised beds are difficult to remedy in practice, unless the powder used is available in narrow particle size cuts.

Unlike the pistol applicators, there is as yet no commercially available fluidised bed system which relies entirely on tribo-charging. Since most fluidised beds are as prone to the detrimental effects of free ions as corona-charged guns, it is surprising that no attempt appears to have been made to exclude ions from the coating enclosure. This would not only virtually eliminate all hazards from high voltage electrodes, but also offer further improvement in particle penetration into electrically screened cavities.

Rough guidelines for good fluidised bed performance might include the following:-

- (i) If possible, choose a system offering safe corona charging electrode configuration.
- (ii) Better coatings will be achieved if the workpiece is small compared to the fluidised bed enclosure.
- (iii) For dipping, the workpiece should be lowered to at least two-thirds of the bed depth. This will minimise changes in powder size distribution due to stratification.
- (iv) Check performance for both negative and positive charging.

OTHER SYSTEMS:

In addition to the traditional pistol and fluidised bed coater systems, a number of more specialist or hybrid designs have been developed in recent years. Some of these systems are available as commercial units, while others have remained as laboratory research

equipment.

For pistol applicators, perhaps the most significant and subtle change has been in the approach to corona charging of particles. As mentioned earlier in this chapter, corona charging offers considerable control over particle charging in a gun. This is achieved, however, at the expense of coating quality. The high density of free, or unattached, ions guarantees rapid onset of back ionization, thus making it almost impossible to achieve high quality coating. However, if the versatility and reliability of corona charging could be somehow combined with the elimination of free ions, then very interesting possibilities arise. This has been successfully achieved by at least two equipment manufacturers²⁰, and results have proved encouraging. The approach to gun design is appealingly simple, but this conceals a subtle and important difference in overall gun behaviour.

Figure 3.4 illustrates schematically the basic differences between conventional corona charged guns and low voltage guns.

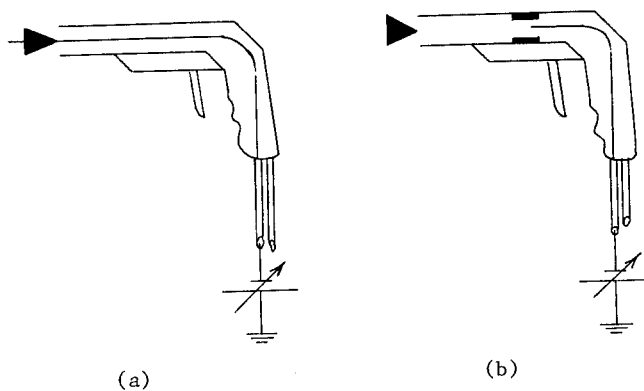


Fig. 3.4 Simplified details of pistol applicators.
(a) Conventional corona charging.
(b) Low voltage corona charging.

In the conventional gun, all the voltage is dropped between the charging electrode at the gun head, and workpiece. Since this spacing can be of the order of 1 metre, or more, relatively high voltages are necessary in order to achieve high enough electric fields at the electrode tip for corona onset. As described earlier, this creates a relatively complex environment in which accurate particle manipulation is attempted. Charged particles will be subjected to both electrical and mechanical forces as a result of interaction with the field and air flow, and this will be further complicated by the effects of high free ion density.

On the other hand, the low voltage gun configuration offers a simpler particle environment. The charging electrode is retracted into the barrel of the gun, and an additional ground electrode is incorporated into the charging region. This effectively replaces the ground offered by the workpiece in the coating booth, and this 'internal' ground can be in close proximity to the high voltage charging electrode. The same high corona onset electric field can therefore now be achieved with a much lower electrode voltage. Reductions from typical operating voltages of about 80 kV, down to about 6 kV, are typical. Considerable gains in size, cost and complexity of the high voltage supply are therefore clear advantages.

Since the corona discharge is restricted and confined to a small volume within the gun barrel, through which all particles must pass, considerable improvement might be expected both in charging efficiency and the overall chargeability (q/m). Comparison tests on high and low voltage guns have indicated the following mean charge-to-mass ratios:-

| | |
|---------------------------|--------------------------------------|
| Typical high voltage guns | $5 \times 10^{-4} \text{ C.kg}^{-1}$ |
| Typical low voltage guns | $10^{-3} \text{ C.kg}^{-1}$ |

In each case, measurements were made using the irrigated grid technique described in Chapter 2, thus eliminating any errors due to free ions. Charging efficiency tests also indicated a marginal improvement using low voltage guns.²¹

All unattached free ions are captured by the grounded counter electrode within the gun barrel, thus eliminating all the free ion population in the region between gun nozzle and workpiece. In many respects, this type of gun creates a charged powder cloud situation which is analogous to that produced by a tribo-charged gun - that is, no free ions. Unlike the tribo gun, however, the low voltage type gun benefits from the advantages of the controllability of corona charging.

Since none of the externally applied voltage is dropped between the gun head and workpiece, it might be reasonable to assume that particle trajectories between the gun head and workpiece were governed primarily by air flow patterns and that no electric field exists between the gun head and workpiece. In reality, the situation is not this simple. Although no free ions traverse the region between the gun head and workpiece, the charged particles emanating from the gun nozzle will themselves create an electric field. Diffusion of particles under the influence of this field will contribute to particle motion, but the overall effect will be small compared to aerodynamic forces. A more intense electric field exists, however, which is not always obvious when first assessing this type of gun.

This electric field arises directly from an electro-gas-dynamic (EGD) mechanism which occurs within the gun barrel itself. Detail of a typical low voltage gun barrel is illustrated in Figure 3.5.

As particles become charged by the corona source and subsequently conveyed down the gun barrel towards the nozzle and diffuser, deposition and accumulation along the inside surface of the barrel and nozzle/diffuser arrangement will occur. This accumulation of charged particles leads directly to a voltage build-up on the nozzle and barrel relative to the grounded counter electrode in the charging region. Generation of voltage in this way is analogous to the moving belt Van deGraaff generator, and a simple mathematical relationship may be used to describe the mechanism.

As accumulation of charge occurs on the gun barrel and nozzle; the potential builds up relative to the corona injector. The

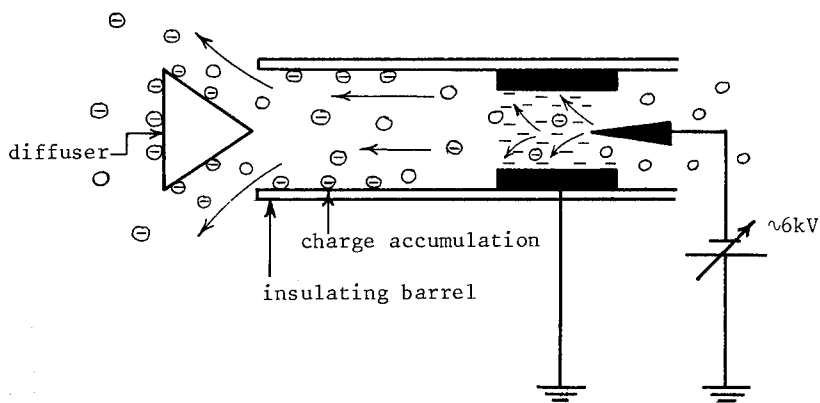


Fig. 3.5 Detail of low voltage gun.

electric field developed between the nozzle and injector exerts a repelling force on further charged particles moving towards the nozzle. Due to the strong coupling that occurs between the charged particles and the air flow, the net charged particle movement may be represented by the expression:

$$v_{\text{charged particles}} = v_{\text{air}} - \mu E \quad (i)$$

where v_{air} is the velocity of the air, μ the mobility of charged particles, and E the local electric field.

The theoretical maximum potential developed on the nozzle may be defined by the condition that charged particles can no longer reach it. That is, the charge carriers remain stationary in the air flow between injector and nozzle. Thus, in equation (i):

$$v_{\text{charged particles}} = 0 ; \text{ and} \quad (ii)$$

$$v_{\text{air}} = \mu E$$

If space charge effects are completely neglected and other field non-uniformities are negligible, it is possible to write E as $\frac{V}{d}$, where V is the generated voltage at the nozzle and ' d ' is the injector-nozzle spacing. Thus, rearranging equation (ii) gives:

$$V_{\text{generated}} = \frac{v_{\text{charged particles}} \times d}{\mu} \quad (\text{iii})$$

Note: This simple theory also assumes that no back ionization occurs within the barrel of the gun as a result of charged particle accumulation.

Equation (iii) is a useful relationship which may be used as a simple guide for gun design. Two easily controllable parameters are the velocity of the charged particles and ' d ', the barrel length. The voltage generated at the nozzle may therefore be enhanced by increasing the gun forward air velocity - resulting in an increase in $v_{\text{charged particles}}$, or increasing the barrel length, or both. This

dependence on barrel length, d , is especially interesting in that it highlights the importance of gun geometry in the achievement of optimized performance. Coating evaluations for egd guns of this type have indicated that superior coating behaviour will be achieved only for a specific barrel length, which in turn implies that a voltage at the nozzle is essential for acceptable performance. This might appear to contradict the conditions conducive to good performance for externally charged corona guns; but the main and important difference between the two systems is that one gun produces a copious supply of free ions, while the egd system delivers a powder cloud completely void of free ions. The implications are, therefore, that a high density of free ions is detrimental to good coating, while the existence of an electric field between gun and workpiece might, after all, be a contributive factor to good electrostatic performance, especially in terms of wrap-around and general improvement in particle trajectory patterns.

An interesting hybrid gun system has been developed in East Germany, and to the author's knowledge no equivalent system is available in the West.²² A schematic of the gun arrangement is illustrated in Figure 3.6.

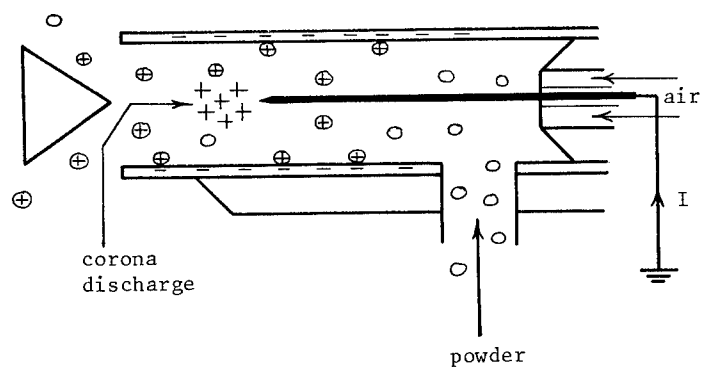


Fig. 3.6 Schematic of corona-assisted tribo gun.²²

Air and powder enter the gun through separate ports. The primary particle charging mechanism is by frictional contact with the inside surface of the gun barrel. A pointed earthed electrode is mounted axially downstream of the powder feed port.

Assuming the powder charges positively by friction on the gun barrel, as illustrated in Figure 3.6, for each positive charge appearing on a particle there will be an equal and opposite negative charge deposited on the internal surface of the barrel. With repeated particle contacts, this negative charge accumulation will be enhanced and will in turn create a high electric field at the sharp pointed end of the earthed electrode. At a sufficiently high local electric field, ionization of the air will occur in the vicinity of the point resulting in the injection of positive (in this case) ions into the air stream. This secondary source of positive charge

enhances the overall charging efficiency of the gun.

The approach is unique in that corona charging is induced in the system without the requirement of a high voltage supply. The proportion of the free ions captured by particles is not clear; this would obviously be an important factor both in terms of particle charging enhancement and overall system behaviour related especially to onset of back ionization.

A typical characteristic of tribo-charged guns is the tendency for particle charging efficiency to decline with continued use. This could be attributed to a number of factors, but most likely to be the result of particle accumulation on the inside surface of the gun barrel - sometimes leading to a partially cured film, or simply an exhaustion of charge exchange sites at the contact interface. This latter suggestion is, however, speculation and little is known about the fundamentals of charge exchange at an interface. Whatever the cause, it is unlikely that this East German gun is immune from these problems, and it is unclear from the published work available²² just how performance will be affected over prolonged periods of operation.

Another interesting approach to dual charging in a gun is the Cyclo-gun marketed by Senkyo-Denkyo of Japan. The approach is different from that adopted in the East German gun, but again both tribo and corona charging have been combined into one gun. The system is illustrated schematically in Figure 3.7. This system is unique in a number of ways. First, the hollow barrel of the gun is itself a small cyclone, thus enabling efficient contact of the powder with internal surfaces. In addition to tribo-charging, two corona charging stations are incorporated into the gun. Details of corona charging at the gun nozzle are illustrated in Figure 3.7(b). The gun is primarily a tribo gun with active supplementary corona charging.

As powder and air enter the cyclone-shaped barrel of the gun, aerodynamic forces result in flow patterns which ensure intimate contact between powder particles and the barrel inner surface. Powder is therefore restricted to a narrow band as shown in

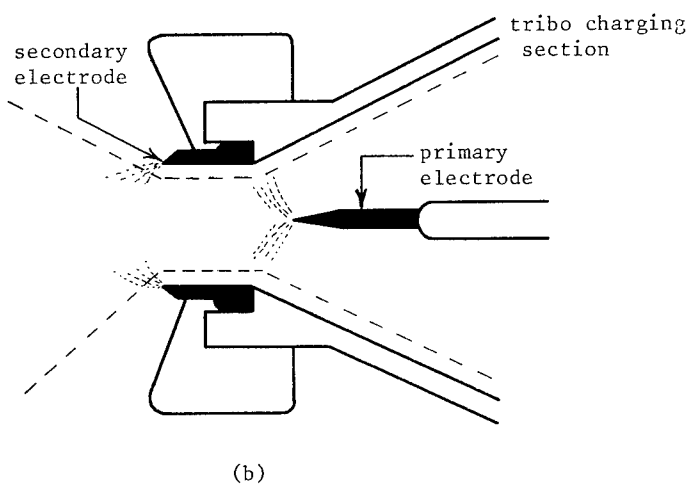
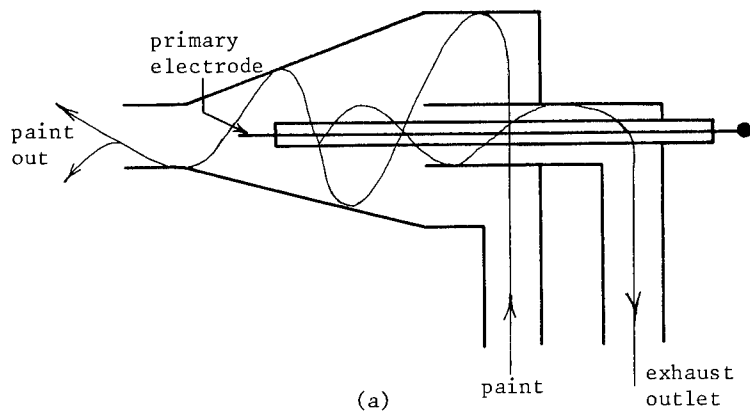


Fig. 3.7 Cyclo-Gun.
 (a) Complete system.
 (b) Detail of gun nozzle.

Figure 3.7(b). Although tribo-charging efficiency must be enhanced by adopting the cyclone geometry, attempts were made at increasing further the overall charging efficiency by adding two corona charging stages. The first corona charging stage is inside the gun nozzle, thus depositing charge on the 'inside' surface of the powder film, while the second corona charging stage is external and charges the 'external' surface of the powder film.

With this design the charging efficiency must be improved, although it must be said that this will be achieved by forfeiting the benefits of superior coating quality associated with ion-free guns. Both the low voltage egd type of guns and tribo guns eliminate free ions, while this system, in addition to being fairly complex, also creates a high density of free ions. Also, in contrast to the East German gun, the polarity of natural charging would require constant monitoring in order to enable the correct choice of corona charging polarity - an operating 'quirk' also shared by the egd gun systems.

In addition to reducing or eliminating free ions in a coating process, it is also sometimes desirable to reduce or limit the air throughput in a gun. As mentioned earlier in Chapter 1, too high an air flow can lead to complete swamping of electrical effects on particle trajectories, leading to deterioration in coating efficiency due to overshooting of the workpiece. In instances where a very low forward component of air velocity is required, techniques are available which enable air-less projection of charged particles - although care should be taken when interpreting the term 'air-less'.

A simple air-less coater might adopt the configuration shown in Figure 3.8. Here, the gun is reduced simply to an inclined plane at the end of which is attached either a needle or sharp blade electrode. Basically, the system resembles conventional externally-charged corona guns. High potential applied to a sharp electrode creates a highly ionized region of air in the vicinity of dispersed powder particles. In the air-less gun, or blade-coater, as it is sometimes known, the only difference is the way in which powder is conveyed to the charging region. Conventional guns suspend powder particles in

an air stream, while in the blade-coater particles are induced into a controlled flow down a vibrating inclined plane.

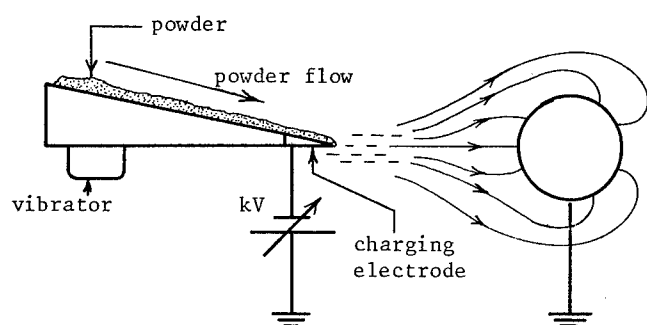


Fig. 3.8 Typical air-less blade-coater.

Once in the vicinity of the charging electrode, the particles become charged by ionic bombardment, and are immediately attracted towards the earthed workpiece. In addition to the charged particle movement, a very high density of free ions will exist between the charging electrode and workpiece, and again under the action of the electric field, movement towards the workpiece will be induced. This flow of relatively high mobility ions will induce air motion from gun head to workpiece, creating an ion wind. This ion-induced wind can, in turn, affect the movement of charged particles in terms of both velocity and trajectories. The ion wind component of velocity can in some circumstances be as high as 2 ms^{-1} , which may be comparable to normal air flow velocities in conventional guns.

Although blade-type guns do not generally use an auxiliary air supply, the deposition process will not therefore be truly air-less.

The blade coater is electrically very similar to conventional corona charging guns. That is, a high potential is applied to an external electrode, and the gun potential is dropped between the

blade head and workpiece. In situations where high electric field effects are required, this technique may have advantages, but penetration into corners and cavities will be poor.

Blade coaters are used where special coating requirements are sought, and are therefore usually installed as 'one-off' custom packages.

An interesting variation of the blade coater is the rotating disc. Here the blade is replaced by a sharp edged rotating disc. A typical commercial system is illustrated in Figure 3.9. With the disc rotating in a horizontal plane, powder fed onto its upper surface will be projected radially outwards under the action of centrifugal forces. With the disc maintained at a high potential, particle charging will be effected at the sharp edge by ionic attachment. The radial motion of particles will therefore be enhanced by both electrical field effects and ion induced wind.

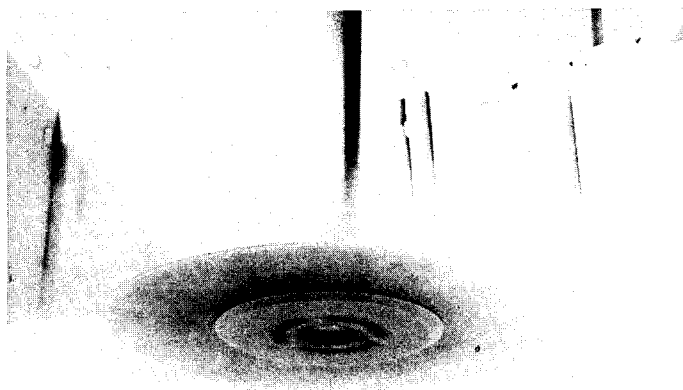


Fig. 3.9 Typical powder disc system.
(photo courtesy G & R Electro-Powder Corp.)

Like the blade coater, this system creates a very high density of free ions, and the entire potential is dropped between the high-voltage disc and workpiece. Rapid onset of back-ionization would therefore be expected, together with poor penetration characteristics. However, penetration may be better than with the static blade system, since particle velocities will be substantially enhanced by centrifugal forces.

Disc coaters appear to lend themselves very well to situations requiring high powder handling rates. The rapid coating of large panels, for example, is possible with just one disc unit. Typical conveyor arrangement might be as shown in Figure 3.10. With a vertically reciprocating disc, and carousel conveyor loop, coating of all surfaces will be possible with the single disc.

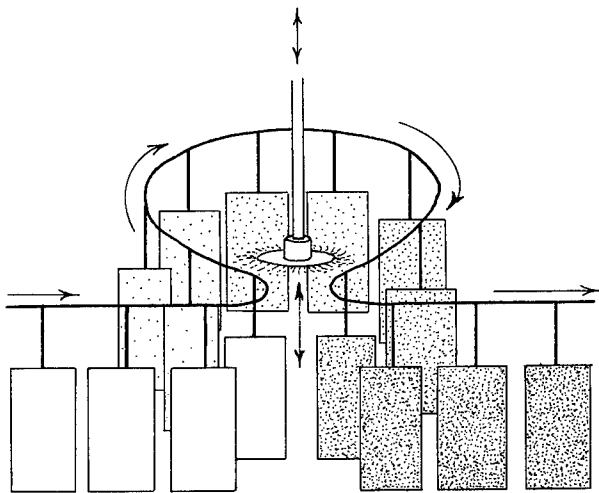


Fig. 3.10 Conveyor loop with disc coater.

COATING BOOTHS

Of all the hardware associated with powder coating, the booth has, until recently, been very much neglected in terms of its importance in affecting coating behaviour and quality. Many commercial booths are still little more than metal boxes - with the only hint of forethought being in the size of the gun ports and other openings relative to the amount of extraction air to be used. As long as no powder escaped the confines of the booth, the system would be acceptable at least with respect to maintaining a clean and particle-free atmosphere at and around the coating line.

It is only relatively recently that more serious consideration has been given to booth design, with special emphasis and appreciation of how the booth itself can be instrumental in determining the overall performance of coating plant.

For example, in a metal booth of fixed dimensions, will there be an optimum size of workpiece for high deposition efficiency? This would seem to be a reasonable supposition. Consider small workpieces in a large booth. The largest and certainly the most dominant earthed object will be the booth itself. Many of the electric field lines originating at the gun head will terminate on the booth walls, with the booth therefore presenting itself as a major competitor for powder deposition. This situation will be highly undesirable in many ways. Coating efficiency on the workpiece will be unacceptably low, and the deposition on the booth walls will extend considerably the time required for powder colour change. Conversely, with a large workpiece relative to overall booth size wrap-around properties will be affected, resulting again in poor coating efficiency and possibly necessitating the doubling of the number of guns necessary to ensure even coating on all sides.

It is possible to estimate the optimum booth size for a particular coating line, and this will be considered in Chapter 4.

Although metal booths are still very much the 'norm' in coating installation, a number of interesting alternatives have recently

appeared on the commercial market. Perhaps the most radical change in booth design has been the introduction of the plastic booth, in hindsight a reasonably obvious choice of material. With the booth itself fabricated of insulating material it no longer competes with the workpiece for particle collection. In fact, the inside walls will themselves become highly charged by ionic collection, and will thus tend to repel approaching charged particles. This will be beneficial both in terms of maintaining clean walls and rapid colour change, and contributing towards an improvement in collection efficiency on the earthed workpiece.

These benefits are only likely to occur when a high density of free ions is generated by the guns; thus, when using the combination of plastic booths and ion-free guns, care should be exercised if improved performance is required. The ion-free guns might offer improvement in coating quality and penetration characteristics, but without charge build-up on the booth walls the plastic booth is unlikely to show a marked improvement in deposition efficiency. Figure 3.11 illustrates schematically the difference in electric field line pattern between metal and plastic booths when used in conjunction with a conventional high-voltage corona charged gun.

An interesting derivative of the plastic booth approach has been the tunnel coating systems. A number of different designs have been available commercially, each with its own special feature. The Volstatic Super Coater was especially interesting in that a number of unique ideas were incorporated into one system. The booth itself was fabricated entirely of Perspex, thus ensuring very high wall resistivities. In addition, the length of the booth was extended thus enabling an increase in residence time of workpieces on a conveyor. There was a specific reason for the latter innovation. Usually, standard high-voltage corona charged guns would be installed in the tunnel booth, but operated at drastically reduced powder feed rates. This in itself offered improved particle charging efficiency at the gun heads, since for the same charge density fewer particles passed through the space charge. With this lower powder feed rate,

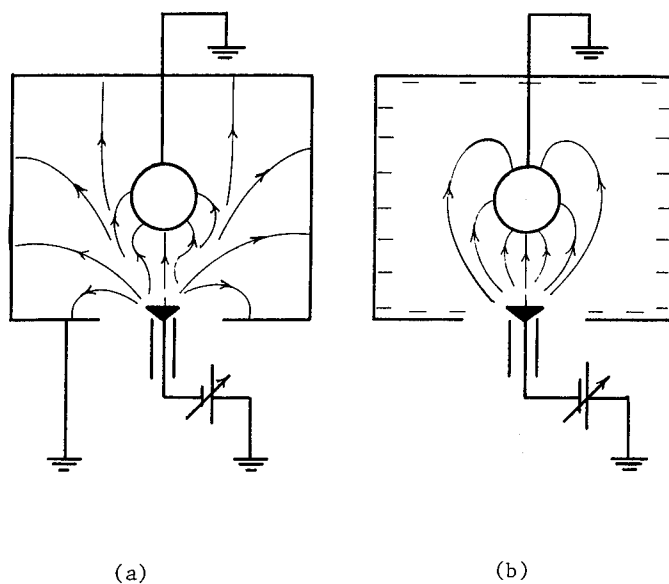


Fig. 3.11 Electric field lines configuration between gun and workpiece.
 (a) Earthed metal booth.
 (b) Electrically insulating booth.

in order to achieve sufficient coating, the workpieces would require extended exposure to the charged powder cloud; hence the introduction of the longer booth. The air flow pattern within the booth was arranged so that the powder cloud was maintained airborne and dispersed for an extended period of time. In addition to the powder guns, secondary charging electrodes were attached in the sidewalls of the booth - downstream of the guns. These are simply sharp pointed electrodes protruding into the booth and connected to a high voltage supply. Copious ion generation by these electrodes ensures post charging of paint particles that may not have been charged at the guns. The base of the booth incorporates a conveyor belt, with a levitating aerofoil at the gun end which helps to keep the powder cloud airborne and re-disperses any overspray that may have alighted on the belt. The conveyor direction is such that workpieces enter

the booth at the end opposite the guns. This ensures that particles that have been airborne for the longest time have first priority in terms of deposition on the workpiece. An important consideration in a system which inevitably will be prone to rapid onset of back-ionization. The high free ion density ensures adequate charge build-up on the walls of the booth, but this is achieved at the expense of a very high density of charge arrival on the workpiece - hence severe back-ionization.

Figure 3.12 illustrates schematically a typical tunnel coating system. Also shown is the air extraction and cyclone arrangement.

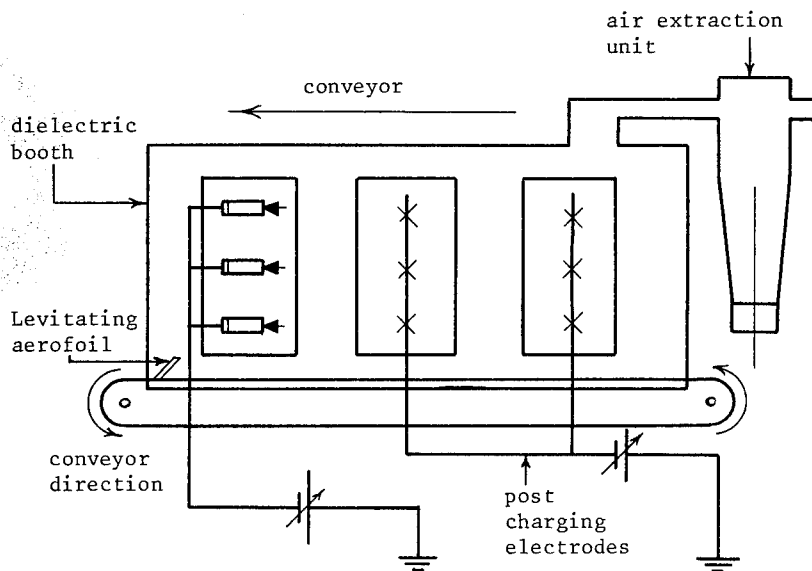


Fig. 3.12 Simplified schematic of Volstatic Super Coater system.

Numerous variations of this coating arrangement have been available commercially, notably one system which has large electrically isolated metallic plates incorporated into the insulating walls of the booth. These plates would rapidly accumulate both charged particles and free ions. Particle collection may be advantageous as

means of precipitating out of the booth all stray particles that would otherwise have alighted on the walls. Ionic collection, on the other hand, results in rapid voltage enhancement of the plates relative to ground. In terms of particle 'focussing' onto the work-piece, some improvement may be gained in deposition efficiency, but at the expense of potentially a very real hazard from flashover and powder cloud ignition. The all-plastic booths may be relatively safe since dissipation of charge over a large insulating surface does not easily occur naturally. However, with large electrically isolated metallic plates, the high capacitance combined with the capability to dissipate all the stored charge in a single event presents a serious safety consideration.

Thus, plastic tunnel booths and post charging electrodes probably represent the most radical change in powder coating hardware. The plastic Super Coater of Figure 3.12 is a true hybrid which almost reproduces the fluidised bed approach. Workpieces remain within the charged powder cloud for an extended period, individual particles are presented with multiple opportunities of being charged, and potentially the system offers very high overall paint utilisation.

More recent innovations are the compact self-contained cartridge booth systems. Insulating material is again used for booth fabrication, but the overall size is generally much smaller than the tunnel arrangement. A unique feature of cartridge booths is that the powder hopper and reclaim system are integrated into one unit. The base of the booth enclosure, where oversprayed powder is collected, forms part of the main supply hopper. Sometimes, this base section of the booth or cartridge is easily detachable and therefore offers relatively rapid and easy colour change. Oversprayed fines are collected in bag filters, with the clean air subsequently returned to the paint shop thus ensuring a closed loop air supply.

As with the tunnel plastic booths, the choice of guns for use in a cartridge booth will be very important. In order to benefit from the advantages offered by the plastic walls, high free-ion density guns must be used; that is, conventional external corona charging

guns.

Cartridge booths are very compact and are therefore very attractive for use in areas where space might be at a premium. As with other systems, however, care should be exercised when assessing their performance, as this can be dictated so much by the size of the workpieces relative to the overall booth size. Since charging of the booth walls will inhibit particle collection and adhesion, rapid and relatively easy booth cleaning will further assist with speeding up colour changing.

The ultimate in booth design would be a system where no particles alight on the walls. In such a system, colour change would be revolutionised and would simply require a change of powder hopper and cleaning of gun feed lines. Technology capable of coping with this extreme requirement is already commercially available in Japan. The technique, known as the electric curtain²³, is technically quite complex; but the hardware is elegantly simple.

The electric curtain is essentially an electrically activated flat surface which enables levitation of powder particles. When energised, both charged and uncharged particles will be unable to alight on the surface. At the present time, electric curtain booths are essentially standard booths which have been lined with tiles of electric curtain elements. The fabrication is illustrated schematically in Figure 3.13. Conducting electrode arrays are imbedded in epoxy resin, with the entire tile surface coated and packaged in ceramic. The actual electrode arrangement and method of energising will not be

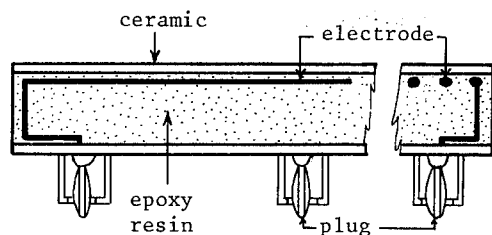


Fig. 3.13 Schematic cross-sectional view of electric curtain tile.

dealt with here, but an important feature is the difference in behaviour between single-phase and three-phase a.c. operation. When supplied with single-phase a.c. voltage, charged and uncharged particles will simply experience a force in a direction away from the tile surface. Levitation will occur, thus ensuring the tile surface will be free of all particles. However, if three-phase a.c. voltage is used, an additional force will be exerted in a direction parallel to the surface of the tile. Thus, in addition to levitation, conveyance of the particles will also be possible.

These two modes of operation are put to use very effectively in a powder coating booth.²⁴ The side walls and back surface of the booth are installed with single phase electric curtain tiles, while a trough at the base of the booth, when energised with three-phase a.c. voltage, will collect and transport the overspray out of the booth and into the re-claim hardware. All this will be accomplished with no powder alighting on any part of the booth wall. The implications of this on colour change are immediately obvious. Figure 3.14 illustrates schematically a typical booth arrangement with electric curtain tiles installed.

Electric curtain panels have been installed in numerous commercial coating plants, where the application is not always to prevent deposition on booth walls.

An interesting example is in powder coating of glass bottles. Here panels installed on the inside walls of the coating booth are arranged in such a way as to optimize the position of the airborne powder cloud after injection by standard corona-charged guns. Figure 3.15 illustrates schematically how this arrangement effectively 'focusses' the airborne cloud in close proximity to the workpiece.

Many new innovations are constantly appearing and being incorporated into commercial hardware. In Japan developments have been particularly significant and will undoubtedly lead to important changes in the entire concept of powder coating. Indeed, there will undoubtedly be many more innovations in the powder coating application equipment

too recent to be recorded here. However, development of electrostatically 'tailored' powders is a much slower process. More fundamental research is necessary to optimize the parameters which affect the electrostatic behaviour of particles. It is probable that further major advances in powder coating techniques will be restricted by the non-availability of such powders.

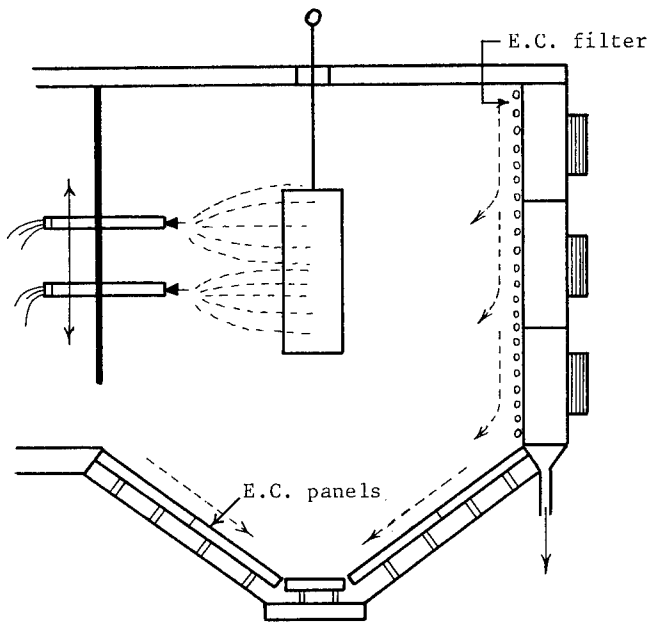


Fig. 3.14 Schematic of electric curtain booth.
(Courtesy S. Masuda, University of Tokyo)

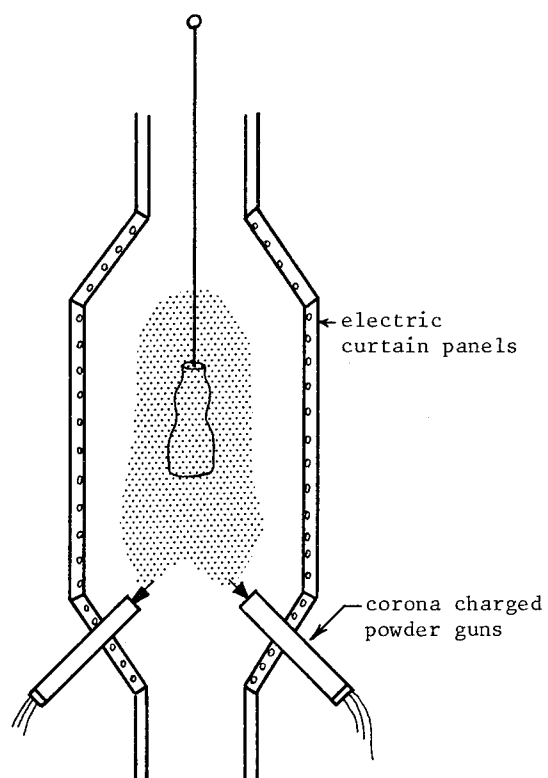


Fig. 3.15 Schematic of bottle coater using electric curtain booth panels.
(Courtesy S. Masuda, University of Tokyo)

CHAPTER 4

System Optimization

System optimization is possibly the most difficult task in the entire process of powder coating. The fact that the performance of any system is dependent on so many variables almost always necessitates a compromise in the choice of parameters. Below is a list of a few variables that require consideration when setting out to design a complete coating system:

- (i) Size and shape of workpiece(s).
- (ii) Size and shape of booth.
- (iii) Booth material.
- (iv) Conveyor speed.
- (v) Type and number of guns.
- (vi) Powder to be used.
- (vii) Colour change requirements.
- (viii) Powder feed rates.
- (ix) Quality of coating.

For most applications, there will be constraints on the choice of an idealised system. For example, there will be a finite choice of booth and gun arrangements, and usually the choice of powder will be restricted by the type and quality of finish.

What are the initial considerations when setting up a system, excluding possible financial constraints? Obviously, the booth/gun arrangement will have to be physically big enough and fast enough to handle the proposed throughput of workpieces. Coating efficiency should be as high as possible, requiring the minimum re-claiming and

re-blending. The quality of the finished product should meet the required standards.

Most commercial equipment, when set-up for demonstration purposes, will meet these requirements convincingly. However, many will behave very differently after prolonged use in the paint shop. The reasons are not always easily identifiable, and often other more definitive factors must be carefully evaluated.

During equipment demonstrations, the following points should be considered:

- (i) Is coating behaviour consistent for different shapes and sizes of workpieces?
- (ii) Assess the coating behaviour for different gun voltages, if corona-charged guns are used.
- (iii) Assess the coating behaviour for different powders if tribo-charged guns are used.
- (iv) Coating behaviour should be assessed after a period of about four hours of continuous operation.
- (v) Assess the coating behaviour for different gun currents if constant current facilities are available.

Most of these points can be assessed by direct observation of coating behaviour, when much useful information is obtained. However, assessment should not end here. If possible, measurement of key parameters should be made at different times during the coating demonstration. Important measurements, which are not difficult to make, should include:

- (i) Identification of the sign of the natural tribo-charging component of the powder. This is important, especially in corona-charged guns, where the sign of the corona-charging should be matched to the sign of the tribo-charging.

The measurement is quite straightforward, and requires only a standard electrometer charge measuring instrument or a field mill.

In a corona-charged gun system, the following sequence could be adopted as a simple guide:

- (a) Switch-off external power supply to gun head.
- (b) Attach sample workpiece to electrometer input, or alternatively, use a field meter as a remote sensor.
- (c) Switch on the powder and air feed and coat the workpiece.
- (d) Determine sign of naturally-charged powder.

This important but simple measurement could have important implications in system behaviour.

If the natural charging of the powder is negative, then the corona charging should be negative, and likewise for positive charging. Some materials can have significant tribo-charging characteristics, which in extreme cases could nullify the corona charging. Obviously, a choice of appropriate polarity would be desirable.

Although most commercial corona-charged guns are produced with negative charging, some manufacturers are offering a choice of polarity. At the present time, the choice appears to be 'either-or'. A gun offering reversible polarity might be an interesting proposition, especially for the user who may wish to use his equipment with a variety of powders. However, currently the operational advantages of this type of gun are apparently outweighed by the cost penalties incurred in installing reversible polarity high-voltage supplies.

- (ii) Check powder resistivity at intervals during the demonstration. Portable equipment which enables rapid and easy measurement of resistivity is now commercially available (see Chapter 2). Multiple checks are advised especially in a demonstration unit which includes re-claim and re-blending. The characteristics of the powder will change as re-claimed powder is added to virgin powder, and it has been found that resistivity is especially sensitive to the percentage doping of re-claim to virgin. Since resistivity appears to be closely associated with chargeability, changes occurring in the powder over a prolonged period of operation will be very important.

Different systems will have different effects on powder deterioration associated with re-claim. The nature of changes in the powder is not clearly understood. Certainly the powder size distribution changes, probably due to a combination of mechanical damage to individual particles and preferential deposition of specific sizes. However, it is more surprising that the chargeability of re-claimed powder will, in many cases, be very different to the chargeability of virgin powder.

This simple measurement of resistivity can therefore give a valuable indication not only of change of resistivity, but also of general coating efficiency and more importantly, how much electro-mechanical modification is imposed on the powder by the system under test.

- (iii) A measure of the charge-to-mass ratio of the powder is always a useful test. Again, portable equipment is available (see Chapter 2), which enables this parameter to be measured relatively easily - at least when tribo-guns are being assessed.

The measurement simply requires the capture of powder sample in a Faraday enclosure which is in turn connected to a charge measuring instrument. This should be done while the gun is set to normal operating conditions. An accurate balance will be required to weigh the captured powder sample - from which the ratio of charge-to-mass may then subsequently be calculated. When assessing corona-charged guns, considerably more care is required in ensuring that no free ions enter the Faraday sample holder - in which case an erroneously high value of charge will be measured.

Accurate measurements will only be possible by using the irrigated grid method; but a good rough indication may be gained using commercial dry grid ion traps. Powder sample collection times should then be restricted to just a few seconds between grid decontamination.

Rigorous testing under laboratory conditions has indicated a marked deterioration in charge-to-mass ratio with coating time, when re-claimed powder is added to virgin powder.²⁵ There would appear

to be a correlation between the resistivity modification and the change in charge-to-mass ratio, with the degree of modification being dictated by the choice of powder/coating system combination.

A charge-to-mass ratio of the order of $10^{-3} \text{ C.kg}^{-1}$ will normally ensure good deposition characteristics. If this value can be maintained, together with a resistivity in excess of about $10^{12} \Omega\text{m}$, then good electrostatic deposition should be expected.

The all-important test is to ascertain whether the original resistivity and values for charge-to-mass ratio can be maintained in a system after a few hours of continuous operation. If they are consistent for the particular powder/coating system under evaluation, it may be confidently assumed that good quality coatings will be possible. However, it does not imply that efficient coating deposition will always necessarily be guaranteed.

Once a system has been found which meets the general coating requirements in terms of workpiece throughput, physical size of equipment, number of guns required, etc., the real problem of system optimization begins.

The plant designer should be in possession of at least one of each type of diagnostic equipment mentioned in Chapter 2.

Essential tools of the trade should include:

- (i) Powder resistivity test cell.
- (ii) Charge-to-mass ratio equipment.
- (iii) A field mill or field probe.
- (iv) Current measuring instrument.
- (v) High-voltage measuring instrument (up to 100 kV).
- (vi) Earth testing equipment.
- (vii) Air speed indicator.

Assuming a standard metal booth/corona-charged gun system was to be evaluated, setting up procedures might include the following tasks:

BOOTH AND GUN AIR

In any open-fronted booth, a negative air pressure must be maintained at all times if powder leakage into the surrounding environment is to be avoided. This is a basic requirement which must be ensured prior to any other setting-up procedure. In addition to simply ensuring the maintenance of negative pressure, the actual air velocity in the vicinity of the gun port and workpiece will be an important factor in determining particle trajectories. Ion wind and gun forward air velocities have been found to be comparable, and typically can be of the order of a few metres per second. These latter two components of velocities can, to some extent, be controlled and used to advantage when certain coating behaviour is required. Ideally, therefore, booth air velocities at the gun head and workpiece should be arranged to be well below a few metres per second. If not, particle trajectories may well be dominated by the effects of the fixed and uncontrollable booth venting system.

Control of gun air will normally be easier, at least in conventional corona-charged guns, where both forward air velocity and in some cases the air flow pattern may be adjusted. This may not be the case in tribo-charged and air-less coaters. Air flow characteristics may be less flexible in tribo-guns, since the prime consideration will be powder flow patterns within the guns optimized for maximum powder charging. In air-less guns, on the other hand, the forward air velocity component will be that solely due to ion-induced wind. Any attempt at changing this will necessitate a change in the corona discharge, leading ultimately to inconsistent powder charging characteristics.

In almost all powder coating arrangements, the ideal air flow pattern will invariably be where the forward air velocity is just sufficient to convey the airborne particles to close proximity of the workpiece surface. As soon as particles are within about 2 cm of the substrate, air flow effects should be at a minimum, and electrostatic attraction forces begin to predominate, thus completing the ideal trajectory with particles alighting and adhering to the

workpiece surface. In order to ensure adequate wrap-around, turbulent air flow should be induced in the vicinity of the workpiece, but with forward air velocities minimised wherever possible.

This general rule of thumb will hold for most workpieces, but exceptions will arise with some special shapes. For example, when coating of the inside of deep cavities or corners is required, an abnormally high forward air velocity will be beneficial. The Faraday cage effect will normally prevent access of charged particles into such areas purely by electrical propulsion forces. Mechanical propulsion by means of a high forward air velocity must therefore be used in order to overcome this screening effect, which incidentally will be more pronounced in corona-charged high-voltage guns with external charging. Optimization of coating performance will only be achieved as a compromise between acceptable deposition efficiency and coating quality. Inevitably, it will be difficult to achieve high deposition efficiency when internal coating of cavities is required.

A lower forward air velocity may be acceptable when using tribo-charged or low-voltage internal-charging guns. These types of guns may therefore offer considerable advantages over external-charging high-voltage guns, and should be given serious consideration in applications necessitating coating penetration.

GUN VOLTAGE AND CURRENT

Commercial equipment often includes a voltage indicator on the front of the gun control panel. Invariably, this will be a measure of the output voltage of the high voltage generator.

It is easy to misinterpret this indicator as being the voltage of the gun charging electrode. During setting-up procedures, and indeed for spot checking, a simple high-voltage measuring probe is always very useful (see Chapter 2). An indication of the true charging electrode voltage may be gained simply by contacting the probe with the gun electrode. Some probes will even work without physical contact, as long as their sharp metallic tips are in close proximity to the high voltage electrode. The tip itself will corona discharge,

as a result of geometrical field intensification, resulting in the end of the probe being raised in potential to approximately the same value as the gun potential. A useful feature when access may be restricted. This measurement is especially important if the condition of the high-voltage cable between generator and gun is in doubt. A broken cable could mean zero potential at the gun head, with the voltage indicator on the control panel indicating normal voltage output.

The current indicator on the gun control panel will generally be a measure of the current supplied by the high-voltage generator. Usually this current will be measured in the earth return line of the generator, and will be equivalent to the corona current at the gun head. Clearly, the gun voltage and current will be interrelated, except when guns are equipped and operated on a constant current mode.

In order to optimize powder charging in a corona-charged gun, powder flow rate will also play an important role in charging efficiency. For a constant current, an increase in powder flow rate will invariably lead to a reduction in charging efficiency. The temptation then would be to increase gun current accordingly. This may increase marginally the charging efficiency, usually at the expense of accelerating the onset of back-ionization due to the increased density of free ions.

Therefore, the choice of gun voltage and current will almost always necessitate a compromise between an acceptable level of charging efficiency and the coating quality in terms of layer disruption from back-ionization.

The best approach in this situation might be first to set up the equipment such that coating behaviour appears visually acceptable. At the chosen gun voltage and current, a check on particle charge-to-mass ratio will then confirm whether, electrostatically, the system is close to optimum performance. If the charge-to-mass ratio falls to the order of 10^{-4} C.kg⁻¹, then charging efficiency will be poor, leading in turn to poor deposition efficiency.

Using the screened Faraday cup for charge-to-mass ratio, measurement will give mean values of charge-to-mass ratio, which in most applications will be quite adequate and useful in terms of determining system operation. This measurement will not, however, indicate the proportion of the powder emanating from the gun that will carry sufficient charge to be considered as potentially collectable on the workpiece. There is a subtle difference between this measurement and straightforward mean charge-to-mass ratio measurement. If an indication of the proportion of charged to uncharged powder is required, then the irrigated screen/L-shaped electrode technique described in Chapter 2 will have to be used.

In terms of coating performance and efficiency of deposition, this will be the all-important parameter.

Charging efficiency may be defined in a number of ways, and care should be taken when interpreting this parameter. For example, charging efficiency could be thought of as a measure of the degree of particle charging relative to the Pauthenier limit. Although, academically, this would be an interesting measurement, its practical relevance would be of secondary importance compared to the L-shaped electrode measurement.

EARTHING

Earthing of workpieces onto metal conveyor lines would appear to be a relatively straightforward procedure. Jigging can, however, pose a serious problem when earth continuity is to be maintained over a prolonged period of operation. Most jigs are metal hangers or hooks of varying shapes and sizes. There will normally be no problem with a clean jig and uncoated workpiece. However, this situation rarely exists in practice. The jigs themselves become coated and subsequently cured during passage through the oven. Earth continuity with a plastic coated jig may not be maintained so easily when used for multiple passes.

Since many jigs are simply sections of small diameter metal rods bent into an appropriate shape, preferential coating of the jig will

not only lead to rapid deterioration of workpiece earthing, but also to serious disruption of the overall coating performance. Previously coated jigs will support rapid onset of back-ionization, leading to a collapse in charging efficiency.

Both size and shape of jig will also be important in terms of trajectory perturbation, and potential electro-mechanical screening of localised regions on the workpiece surface.

Continuous checking of jig earthing is not difficult, and equipment is available commercially for automatic monitoring.¹⁷ What are more difficult to monitor and control, however, are the continuously varying effects of a slow but steady growth in jig coating thickness.

The choice and optimization of a particular booth/gun combination involves considerable effort which will be wasted if no consideration is given to jig design. For example, if the jig is large compared to the workpiece, then parasitic coating will almost certainly occur. Sharp bends, corners, edges and points should be avoided whenever possible. These geometries will not only exaggerate electric field modifications, but will also encourage preferential coating at the expense of the workpiece. With respect to earth continuity, there are two useful 'rules-of-thumb' which can promote improved performance. The first, and most obvious, is to arrange, whenever possible, for contact between jig and workpiece to occur where either no powder deposition is required, or where coating thickness and quality is not important. For example, on the inside of a casting where external coating is primarily for aesthetic purposes. The second is to arrange for the point of contact between the jig and workpiece to be a sharp point. This not only minimises the inevitable, undesirable jig marks, but also ensures electric field intensification at the point of contact if the sharp point is coated. Under these conditions, particle and ionic accumulation on the workpiece will result in the voltage of the workpiece being raised above ground zero. With a sharp point contact, intensification of the field between workpiece and jig will ensure a breakdown across the contact point at a relatively low workpiece voltage. The creation of such a

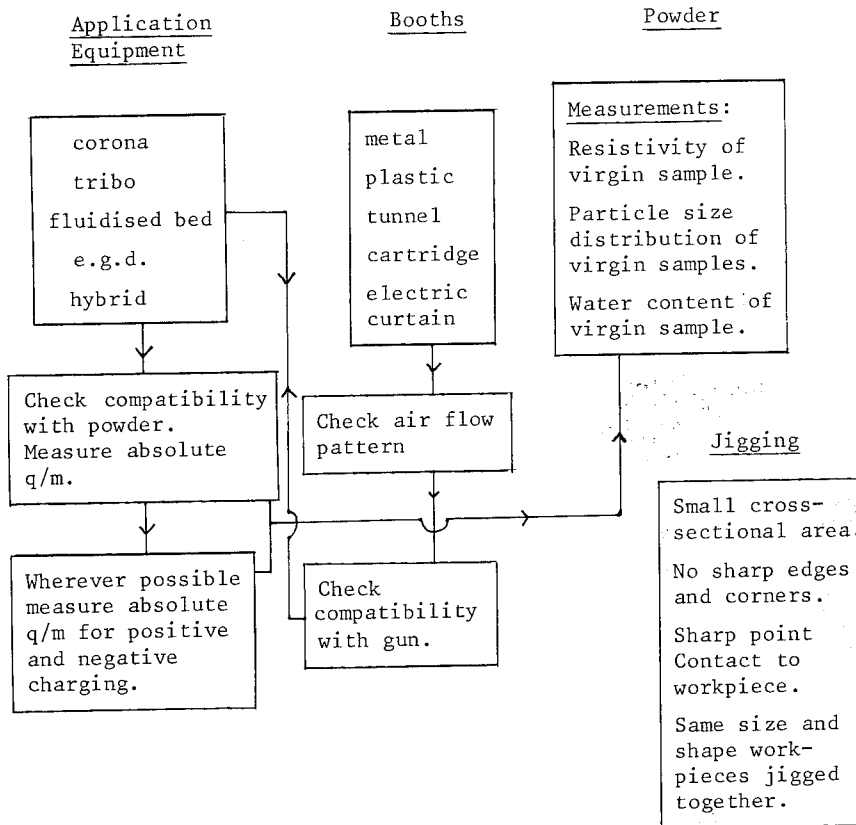
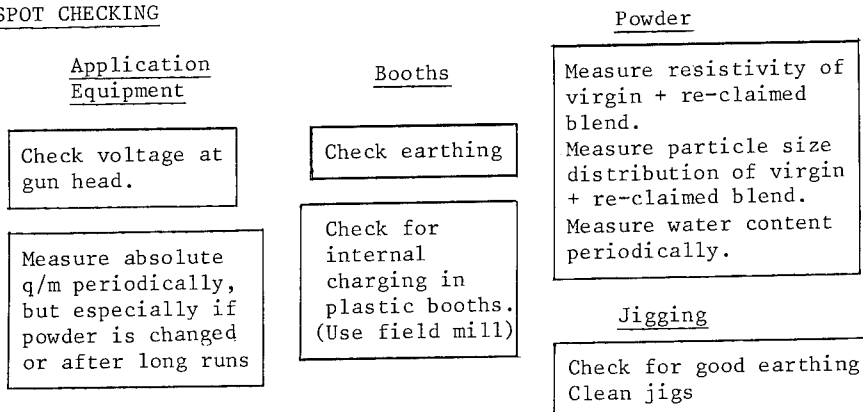
breakdown, and possibly a tracking path, will normally be sufficient to ensure earth continuity even for relatively thick layers of jig coating.

Table 3 lists some of the important considerations relating to jiggling optimization.

| <u>Good Jigging Practice</u> | <u>Poor Jigging Practice</u> |
|--|---|
| Jig should be a good conductor. | Poor conductor. Heavily coated jig. |
| Overall dimensions small compared to workpiece. | Large jigs supporting small well-spaced workpieces. |
| No sharp bends, points or corners. | Sharply angled sections used for jigs. |
| Jig contact to workpiece by sharp point. | No consideration given to jig/workpiece connection. |
| Workpieces of similar shape and size jiggled together. | Mixture of workpieces on same jig. |
| Regular cleaning of coated jigs. | No established jig-cleaning programme. |

TABLE 3. Hints on how to improve workpiece jiggling.

Inevitably, coating requirements will differ from plant to plant, and for that reason it is almost impossible to draw a universal optimisation programme. However, with careful planning and an appreciation of the implications of basic electrical parameters, it is often possible to achieve considerable improvement in plant performance. A rough guide to system optimization is illustrated by the following flow chart.

SETTING UPSPOT CHECKING

It is always useful, both during demonstrations, setting-up and on-line spot checking, to be familiar with at least the orders of magnitudes of the relevant electrical parameters. Listed below are some of the more important 'rule-of-thumb' numbers.

| <u>Resistivity</u> | <u>Charge-to-mass ratio</u> (q/m) |
|---|---|
| For acceptable adhesion. $> 10^{12} \Omega\text{m.}$ | $\approx 10^{-3} \text{ C.kg}^{-1}$ |
| Excellent adhesion but probably difficult to charge efficiently and rapid onset of back-ionization with corona-charged guns. $> 10^{15} \Omega\text{m.}$ | Poor electrostatic behaviour $< 10^{-4} \text{ C.kg}^{-1}$ |
| Excellent charging but poor adhesion. $< 10^{11} \Omega\text{m.}$ | |
| Compromise resistivity for generally good charging and acceptable adhesion. $10^{12} \Omega\text{m.}$ | |

CHAPTER 5

Future Trends

EQUIPMENT

The ultimate goal for almost all powder coating applications is the ability to deposit a thin, even thickness, high quality coating as efficiently as possible. Some systems already come close to achieving this, but usually only at the expense of system flexibility. That is, if the same gun, booth, powder and workpiece combination is to be used over a prolonged period, then the system may be optimized to give good performance. In order to maintain optimization, however, spot checks will be required at pre-determined intervals. Gun charging might change with variation in powder blend of re-claim to virgin, for example; and this would require periodic checking.

What is more difficult to achieve, however, is the maintenance of optimized performance when conditions on the coating line change; for example, regular powder colour or type change and different workpieces. Under such varied conditions, there will be little chance of achieving optimal performance, and normally the procedures for setting up the system will involve trial and error. Important electrical parameters will rarely be measured, and under such circumstances the advantages associated with electrostatic deposition will often be lost.

It appears likely that there will be increasing use of plastics for booth fabrication. At the present time, however, booths still appear to be nothing more than plastic boxes. Electrical optimization of plastic booths will undoubtedly lead to an improvement in performance,

and computer modelling techniques already make accurate predictions of system behaviour possible under varying conditions.

Low voltage egd guns have certainly contributed to improvement in powder charging, and have led the way in a totally new approach to coating techniques. Since some guns can contribute a substantial tribo component of charging, it is possible that a future system could usefully incorporate a polarity sensor coupled with a reversible polarity power supply. Any change in polarity due to a change in powder would then automatically be catered for, with the 'correct' choice of corona charging polarity always ensured. In fact, for low voltage guns, this is by no means an impossible feature, but is a refinement which perhaps would be difficult to justify in terms of cost.

Tribo-charged guns are potentially very attractive, but they will probably not displace corona-charged guns, at least until a more fundamental understanding of charge exchange at an interface will allow more controllable operation. It is doubtful whether this will be possible in the immediate future.

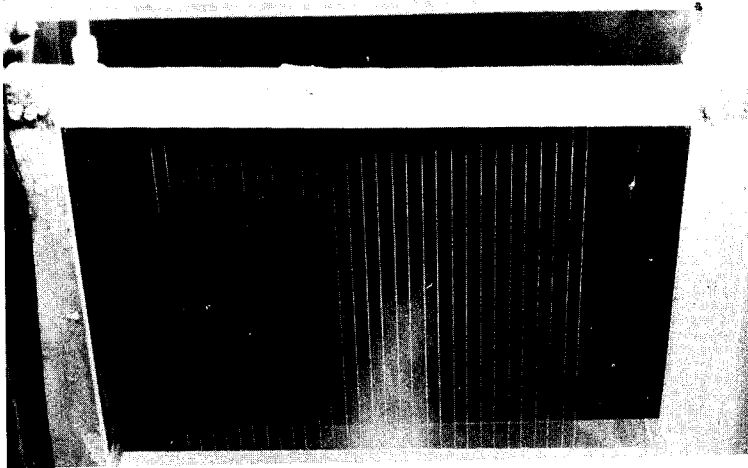
The concept of the plastic booth appears to be gaining interest, and potentially has interesting possibilities provided careful modelling of the system is carried out in order to ensure optimum performance. Computer-aided design approaches are discussed later in this chapter.

An improvement in coating quality is constantly sought. Perhaps the one characteristic of powder coating which makes this difficult to achieve in practice is the apparent ease with which back-ionization is initiated on deposited powder layers. With conventional corona charging, both in pistol and fluidised-bed applicators, the high density of free ions alighting on the deposited powder layer ensures the onset of back-ionization as soon as the first layer of powder is deposited. The resulting damage to the layer manifests itself by way of pin holing and severe cratering, which ultimately leads to the familiar orange-peel surface finish. As was described earlier, tribo-guns and low voltage guns do not readily display

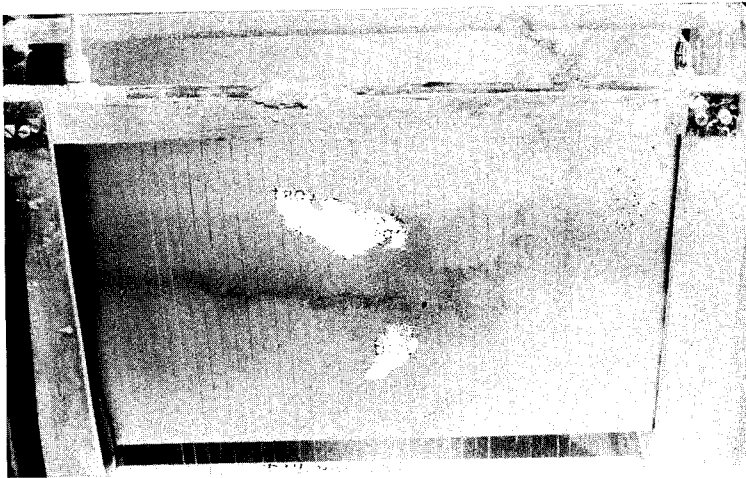
these unattractive performance features - due primarily to the absence of free ions in the deposition process. However, both tribo and low voltage guns also display operating characteristics that can severely affect their performance, and thus do not offer complete immunity from trouble-free operation.

One possible alternative approach to overcoming the detrimental effects of free ions might be a system which incorporates the irrigated grid equipment described in Chapter 2.^{14,15} This technique was developed specifically to enable the absolute measurement of charge-to-mass ratio in a corona-charged powder system. However, during experimental evaluation and routine use over an extended period, the incorporation of an irrigated grid into a pilot corona-charged pistol coating system demonstrated its effectiveness not only in the removal of free ions but also in the superiority of the coating quality. Figure 5.1 illustrates the dramatic difference in coating performance and the importance of free ions in terms of initiation of back-ionization, ultimately leading to a complete collapse of electrostatic charging at the gun head. In Figure 5.1(a), the grid ion-trap is placed between gun and flat sheet workpiece. The grid is dry and therefore accumulates charged powder particles in addition to ions. Within a few seconds, back-ionization is initiated on the coated grid itself, thus discharging further oncoming powder from the gun. No or very little powder is therefore electrostatically deposited on the matt black painted flat sheet collector plate. With grid irrigation, as in Figure 5.1(b), no back-ionization occurs on the grid; high powder charging is maintained at the gun head, and rapid high quality coating of the collector plate is achieved. This test not only demonstrates the effectiveness of the irrigated grid in capturing free ions, but also illustrates so well the detrimental effects of back-ionization in terms of deposition performance.

Future development of the irrigated grid technique may well lead to specialist coating systems where high quality, reproducible, layer deposition is sought. The grid may not necessarily be water



(a)



(b)

Fig. 5.1 Irrigated grid showing effects of back-ionization on layer deposition.
(a) Dry grid. Back-ionization.
(b) Irrigated grid. No back-ionization.

irrigated. Tests are already under way to evaluate the possibility of maintaining the grid wires free of powder by electrical and acoustical excitation. Such a system would lend itself very easily to incorporation into a full scale commercial coating plant.

POWDERS

In addition to optimization of equipment, there is currently tremendous scope for electrostatic optimization of powders. Most, if not all, powders are currently formulated for optimum performance in terms of flow, finish, etc; with little or no concern about electrical parameters and how these might affect electrostatic behaviour. That is, there is no electrostatic optimization. This must create a weak link not just in powder behaviour, but in the behaviour and optimization of a complete coating system. For example, hardware may be painstakingly optimized, but to no purpose if the electrical parameters of the powder to be used are not conducive to accepting charge.

Just how individual electrically insulating particles acquire charge from airborne ions is not at all clear. A knowledge of the actual ionic attachment sites, for example, would be of considerable importance as the first step towards optimizing charge acceptability. This inherent difficulty of charging insulating particles was highlighted by Masuda in his work on electrostatic precipitation, which ultimately led him to the development of the boxer charger.²⁶ Rather than relying on unipolar charging of particles from a single ion source, the boxer charger generates unipolar ions from what is effectively two sources, with ionic motion being in opposing directions. As insulating particles are made to pass through the ionized region, ionic bombardment is effected over the entire surface area of each particle. This has been shown to dramatically increase the level of charging on individual particles.

Although an important innovation, high charge level per particle is not perhaps the ultimate requirement for powder coating applications. A charge-to-mass ratio of, for example, 10^{-3} C.kg⁻¹ is not difficult to achieve with corona charging. More important, and more

difficult to achieve, is this value for each and every particle in a typical powder cloud emanating from a gun head. If the charging efficiency is to be substantially improved, it is possible that a completely new approach will have to be adopted for powder charging.

Present day equipment incorporates one of two principal charging methods: corona charging or tribo-charging, and the relative advantages of these two techniques have been discussed in previous chapters.

There is a third and potentially very attractive alternative to these two methods: a method that has been adopted and optimized to suit the requirements of particle handling in electrophotographic copiers. Conventional electro-copiers use a dry powder developer which usually comprises two components: relatively large (100~200 μm) carrier beads and smaller (≈ 30 μm) toner particles, attached to each other by electrostatic forces resulting from interface charge exchange. Typical of such charging mechanisms (tribo), the level of charge exchange will be dictated primarily by the interface conditions, and will offer little controllability. More modern developers or toners are single component systems, where the complexities of the carrier/toner interface are eliminated. No carrier particle is used, and charging of the toner is effected by an artificially created electric field. As the toner particles emerge from a dispenser, an external electric field is created between the particles and the substrate upon which they will alight. Particles are charged by induction; an appealingly simple mechanism which offers infinite controllability without the necessity of producing free ions.

Of course, electrical parameters have to be exactly right if this technique is to work, and obviously toner manufacturers have concentrated on the electrical parameters of toner particles, as well as on other requirements relating to copy performance and quality. For electro-copiers, the resistivity of the toner has been arranged to be field-dependent, and the same concept would be required for powder coating applications.

For example, at the charging station the resistivity of the particles should be as low as possible for efficient charge exchange by induction. However, on transfer to the substrate, whether it be a photoconductor of a copier or a food mixer casing, the resistivity should be as high as possible if adequate adhesion is to be ensured.

Careful attention to the chemical make-up of the toner has made this possible for electro-copier applications. Although it is not immediately obvious how this could be achieved for powder coating applications, it is worth noting that such techniques do exist and indeed are commercially exploited. That similar consideration might be given to dry powder paint should not be discounted, provided powder manufacturers are willing to invest in the future by initiating fundamental research investigations. Toner manufacturers have shown the way, and have proved that electrical manipulation and optimization of solid particles can be achieved.

Induction charging in powder application equipment would certainly be a very attractive proposition. The technique would offer infinite controllability over charging levels, elimination of free ions and operation at low charging voltage. Induction charging could be easily adopted for use in either standard pistol-type or air-less blade-type applicators (see Chapter 1).

The ultimate requirement in most coating installations is the ability to deposit a high quality coating as thinly as possible. Coating thicknesses of around 50 μm would often be considered very desirable. However, with mean powder particle sizes being of the order of 100 ~ 150 μm , such coating thicknesses have always been beyond reach. Only very recently have new generations of ultra-fine powder particles been commercially available, which for the first time offer the possibility of thin layer deposition. Orgasol²⁷, a nylon based material with mean particle diameter of 15 μm , is an interesting example of this new generation of fine powders. In addition to offering very small particle size, the particles are almost spherical in shape, which can be very useful if theoretical modelling of its electrostatic behaviour is to be attempted. As

with all fine particles, however, handling and manipulation will not be easy. The maintenance of a constant flow rate through delivery hoses, for example, will be difficult to achieve, and compaction in silos and hoppers invariably leads to erratic feed rates.

It would appear that problems associated with ultra-fine powders are associated more with their mechanical rather than electrical properties. A solution to the flow problems alone would undoubtedly be a major contribution to the emergence of an entirely new approach to powder coating.

MODELLING

Mathematical and computer modelling of electrostatic powder spraying processes is becoming increasingly important since considerable cost savings may be made by efficient design and operation of powder spraying equipment. With the aid of computer modelling, coating performance for different gun, booth and workpiece combinations can be predicted.

In principle, modelling may be performed on a complete spray system to include both the powder charging processes in the gun and powder motion in the booth. The ease with which changes in equipment geometry and operating conditions can be made makes computer simulation a powerful design tool, and the ability of a simulation to predict performance opens up considerable opportunity for automation of a spraying process.²⁸

Computer-aided design (CAD) models are generally limited in complexity only by the computer resources available. In contrast, control simulations must be performed in real time during actual spraying operations, and must ideally be as simple as possible. However, control programmes may often be based on simplified CAD simulations.

CAD SIMULATION

The movement of a charged particle from the gun head to a workpiece occurs as a result of combined electrical and aerodynamic forces. Over most of the volume of a typical spray booth, aerodynamic forces

will predominate. Close to the booth walls and workpiece surface, however, electrical forces will become increasingly dominant.

Modelling powder motion involves calculation of both motive forces repeatedly during the spraying process, since the distribution of charged powder and free ions will be time dependent. These calculations require considerable computational effort and a number of simplifications must be introduced in order to make the simulation practical. The three-dimensional booth geometry may be approximated to a two-dimensional axisymmetrical cylinder booth. Air-flow due to the powder carrier air may be assumed not to vary significantly during the spraying process. Figure 5.2 illustrates a typical flow diagram of a powder spraying simulation programme.

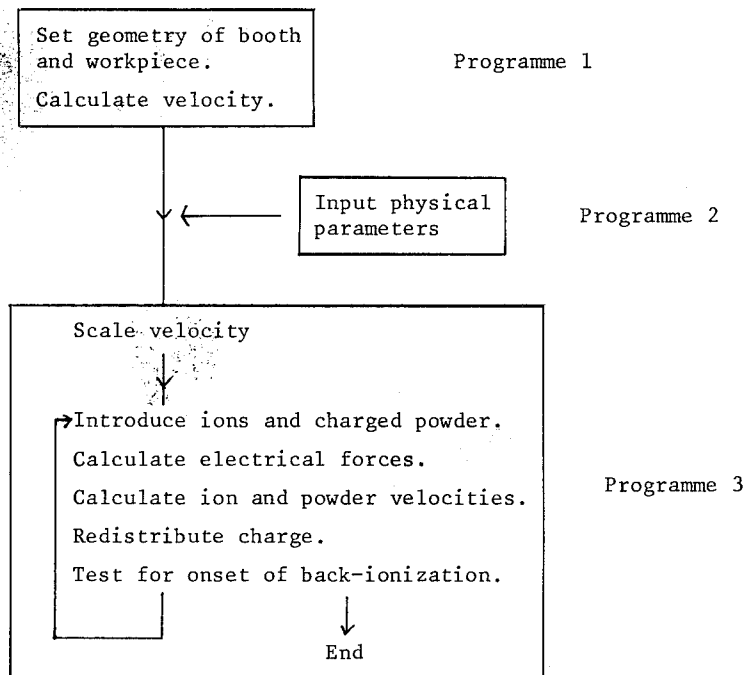


Fig. 5.2 Typical flow diagram for powder coating programme.

It is structured as three discrete programmes, two of which are pre-processes which set the booth geometry, calculate the air-flow and set operational parameters such as charge-to-mass ratio. The remaining programme performs the simulations. The structure of the programme is arranged so that for a fixed geometry, many different simulations may be run with different operational parameters.

Preliminary results of electrostatic powder coating simulation programmes have demonstrated how the presence of free ions in the spray booth can enhance deposition rates over space-charge-free situations, but on the other hand encourages the early onset of back-ionization and degrades the quality of the coating finish. Deposition has been shown to occur faster in dielectric booths than in the traditional metal booth, with deposition rates increasing as the dielectric constant of the booth decreases. The ratio of work-piece size to booth size has been found to be important: the larger the relative size of the booth, the faster the deposition - at least in metal booths. The situation becomes a little more complicated in plastic booths. Finally, the model has led to confirmation of the experimentally observed critical powder resistivity of $10^9 \sim 10^{10} \Omega m$, below which good adhesion is unlikely to occur.

Summary

This book has attempted to highlight some of the more important practical implications of experimentally observed phenomena in powder coating.

Electrically charging isolated particles is not easy, and theoretical modelling of various mechanisms can become extremely complicated. Since the entire concept of powder coating relies on efficient particle charging, this has been dealt with in some detail but mathematical treatment has been kept to an absolute minimum. It was felt that the powder coating industry lacked a simple guide to powder coating, and this monograph has been written with this very much in mind. The chapter on measurement techniques should be especially useful to plant operators. There currently appears to be a serious lack of appreciation of how system behaviour may be assessed and optimized from quite straightforward measurements. Equipment now commercially available allows easy measurement of parameters such as resistivity and charge-to-mass ratio. Plant operators are encouraged to make more use of diagnostic equipment, where familiarisation with both measurement techniques and actual numerical values of various parameters will aid considerably system optimization.

Both hardware and powder are constantly under development, and it is likely that a number of new innovations will have appeared by the time this monograph is published. However, some predictions have been made in the final chapter, including an analogy with formulation techniques in the electrophotography industry. It is possible that

any further dramatic changes in powder coating technology will only be achieved if and when a similar degree of sophistication is introduced into powder formulation techniques. At the present time, there is little or no consideration given to the electrostatic properties of powder paint - a serious omission if complete system optimization is to be achieved.

Bibliography

1. J. F. Hughes. 'Measurement techniques in powder coating installations'. Finishing Industries. Wheatland Journals Ltd. Vol. 4. No. 5. pp. 20-24. May 1980.
2. J. F. Hughes. 'Optimizing powder plant'. Finishing. Wheatland Journals Ltd. Vol. 6. No. 7. pp. 15-20. July 1982.
3. J. F. Hughes. 'Future trends in powder', Finishing. Wheatland Journals Ltd. Vol. 6. No. 11. pp. 17-21. Nov. 1982.
4. J. F. Hughes. 'Trouble shooting on powder installations'. Finishing. Wheatland Journals Ltd. Vol. 7. No. 4. pp. 24-26. April 1983.

References

1. B. D. Moyle and J. F. Hughes. Inst. of Phys. Conf. Ser. No. 66. Electrostatics. Oxford. pp. 155-160. 1983.
2. M. M. Pauthenier and M. Moreau-Hanot. J. d'Physique et le Radium. Series No. 7. pp. 590-613. 1932.
3. P. S. H. Henry. Inst. of Phys. Conf. Ser. No. 11. Static Electrification. pp. 195-199. 1971.
4. D. K. Davies. Inst. of Phys. Conf. Ser. No. 4. pp. 29-36. 1967.
5. C. F. Gallo and W. L. Lana. Journal of Electrostatics. Vol. 2. pp. 145-150. 1976.
6. A. W. Bright. Journal of Electrostatics. Vol. 4. pp. 131-147. 1978.
7. C. S. Athwal, P. F. Coventry and J. F. Hughes. Inst. of Phys. Conf. Ser. No. 66. Electrostatics. pp. 167-172. 1983.
8. G. Coe, J. F. Hughes and P. E. Secker. Brit. J. Appl. Phys. Vol. 17. pp. 885-890.
9. S. Singh and A. W. Bright. 3rd Int. Congress on Static Electricity. Grenoble. pp. 11a-11e. 1977.
10. P. Lorrain and D. Corson. Electromagnetic fields and waves. Freeman (San Francisco). 1970.
11. J. F. Hughes and Y. C. Ting. IEEE/IAS. 12th Annual Meeting. Los Angeles. pp. 906-909. 1977.
12. J. F. Hughes and Y. C. Ting. 3rd Int. Congress on Static Electricity. European Federation of Chemical Engineering. Grenoble. 1977.

13. A. W. Bright, R. P. Corbett and J. F. Hughes. Electrostatics. Engineering Design Guide No. 30. Oxford University Press. 1978.
14. U.K. Patent No. 8320654.
15. B. D. Moyle and J. F. Hughes. IEEE/IAS. 17th Annual Meeting. San Francisco. pp. 1191-1195. 1982.
16. J. F. Hughes and A. W. Bright. Trans. IEEE and Industry Applications. Vol. 1A-15. No. 1. pp. 100-104. 1979.
17. Available from Industrial Development (Bangor) Ltd., UCNW, Bangor, N.Wales.
18. Available from Mindon Engineering Ltd., Nottingham, U.K.
19. Available from Electrostatic Equipment Corporation, Connecticut, U.S.A.
20. Available from Volstatic Coatings Ltd., U.K.
21. J. F. Hughes private communication.
22. W. Kleber et al. Elektrostatisches Beschichten. Vom. 24. bis. 27. Hochschule fur Verkehrswesen. Friedrich List. Dresden. pp. 109-116. 1978.
23. S. Masuda et al. IEEE/IAS 12th Annual Meeting. Los Angeles. pp. 887-891. 1977.
24. Available from Sankyo-Denkyo. Japan.
25. J. F. Hughes. Private communication.
26. S. Masuda. IEEE/IAS. 15th Annual Meeting. Cincinnati. pp. 904-911. 1980.
27. Available from ATO-CHEM, Serquigny, France.
28. N. J. Diserens et al. Journal of Electrostatics. Vol. 5. pp. 169-182. 1978.

Index

- adhesion 31
- back-ionization 20, 22, 23, 27, 30, 63, 76, 94, 98
- bi-polar 21
- blade-coater 79
- booths 56, 61, 69, 82, 83, 96, 102
- charge-to-mass ratio 29, 40, 45, 53, 103
- corona 1, 2, 28, 62, 69, 92, 106
- cyclo-gun 76, 77
- disc 80, 81
- earthing 99
- electric curtain 87, 88
- electric field 17, 29, 35, 44, 54, 58, 72
- electrometer 40
- electronegative 4
- Faraday cage 19, 41, 67
- field mill 54, 58, 59
- fluidised bed 61, 64, 66
- Gauss' Law 19
- guard electrode/ring 32, 33
- induction 12, 14
- ion wind 15, 16, 79
- ions 16, 23, 28, 72
- irrigated grid 43, 107, 108
- jigs 99, 100, 101, 102
- mobility 73, 79
- modelling 112
- optimization 91, 105
- orange-peel 25, 27, 106
- Pauthenier limit 6, 7, 8
- permittivity 35, 36
- pin-holing 25, 27
- pistol 61, 70
- potential 47, 97
- powder 109, 111
- relaxation 30
- resistivity 29, 32, 93, 95, 103, 110
- resistor chain 49, 50
 - time-constant 35
- tribo 8, 9, 11, 12, 28, 63, 75, 92, 106, 110
- wrap-around 19, 20, 52