

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS	iii
ABSTRACT IN ENGLISH	iv
ABSTRACT IN THAI	vi
TABLE OF CONTENTS	viii
LIST OF TABLES	xi
LIST OF FIGURES	xii
NOMENCLATURE AND ABBREVIATION	xvi
CHAPTER 1 INTRODUCTION	1
1.1 Statement and Significance of the Problem	1
1.2 Literature Reviews	3
1.2.1 Enhancement of Submicron Particles Charging	3
1.2.2 Submicron Particle Agglomeration Enhancements	9
1.2.3 Non-Thermal Plasma for Submicron Particle Removal	16
1.3 Aims of the Study	21
1.4 Benefits of the Study	21
1.5 Scope of the Study	21
CHAPTER 2 THEORY	22
2.1 Electrostatic Precipitator	22
2.1.1 Operation Properties of ESPs	22
2.1.2 Corona Discharge	23
2.1.3 Particle Charging Mechanisms	26
2.1.4 Dust Particle Transport	27
2.1.5 Particle Collection Efficiency	32
2.2 Non-Thermal Plasma	33
2.2.1 Plasma Streamer	34
2.2.2 Particle Charging in Plasma	38

2.2.3 Pulsed Corona Plasma	41
CHAPTER 3 PULSED CORONA DISCHARGE FOR ELECTROSTATIC PRECIPITATOR ENHANCEMENTS	44
3.1 Introduction	44
3.2 Theory	45
3.3 Experimental Setup	55
3.4 Results	61
3.4.1 Voltage-Current Characteristics	61
3.4.2 Collection Efficiency of the ESP	63
3.4.3 Effects of Pulse Frequency on Fractional Collection Efficiency	64
3.5 Conclusion	67
CHAPTER 4 AGGLOMERATION OF SUB-MICRON PARTICLES BY NON-THERMAL PLASMA TECHNIQUE	68
4.1 Introduction	68
4.2 Theory	70
4.2.1 Particle Number Concentration Distributions	70
4.2.2 Plasma Agglomeration	72
4.3 Experimental Setup	76
4.4 Results and Discussion	77
4.4.1 Voltage-Current Characteristics	77
4.4.2 Distributions of the Particle Number Concentration	79
4.4.3 Agglomeration of Sub-micron Particles in Non-Thermal Plasma ESP	80
4.4.4 Voltage-Current Characteristics	81
4.4.5 Effect of the Pulse Frequency on the Particle Reduction Efficiency	82
4.4.6 Effect of the Particle Concentration on the Particle Reduction Efficiency	83
4.4.7 Effects of the Gas Flow Velocity on the Particle Reduction Efficiency	84
4.4.8 Modeling of the Agglomeration Efficiency	86
4.5 Conclusions	87

CHAPTER 5 ENHANCEMENT OF ELECTROSTATIC PRECIPITATOR	89
FOR SUBMICRON PARTICLE COLLECTION BY	
NON-THERMAL PLASMA PRE-CHARGER	
5.1 Introduction	89
5.2 Experimental Setup	90
5.3 Results and Discussion	91
5.3.1 Effect of the Enhanced NTP Pre-charge on Collection Efficiency of Wire-Cylinder ESP	91
5.3.2 Effect of Supplied Voltage on Overall Collection Efficiency of the Wire-Cylinder ESP with NTP Pre-charger	92
5.3.3 Effect of the Dust Loading on Overall Collection Efficiency of the Wire-Cylinder ESP with NTP Pre-charger	93
5.3.4 Modeling of the Overall Collection Efficiency of the Wire-Cylinder ESP with NTP Pre-charger	94
5.4 Conclusions	95
CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS	97
6.1 Pulse Corona Discharge for Electrostatic Precipitator Enhancements	97
6.2 Enhancement of Electrostatic Precipitator for Submicron Particle Collection by Non-Thermal Plasma Pre-charger	97
6.3 Recommendation and Future Works	99
REFERENCES	100
APPENDICES	106
APPENDIX A: Design of Pulse-Energized ESP and Power Supply	107
APPENDIX B: Computer Program for Estimate Migration Velocity	114
APPENDIX C: Data Sheet	120
APPENDIX D: Experimental Data	146
APPENDIX E: List of Publication	190
CURRICULUM VITAE	221

LIST OF TABLES

Table	Page
2.1 The overview of non-thermal plasma type and their most common applications	33
3.1 The parameters for calculating the number of charge on surface area of particles	48
3.2 Criteria and requirements used in the design of the wire-cylinder ESP	54
3.3 Testing conditions of the designed ESP	54
4.1 Basic parameters of the ESP	77
4.2 The particle reduction efficiencies with various pulse voltages. The dust loading and the pulse frequency were 5×10^5 particles cm^{-3} and 20 kHz, respectively. The gas velocity was 1 ms^{-1} .	82
4.3 The particle reduction efficiency with various pulse frequencies. The particle concentration was at approximately 5×10^5 particles cm^{-3} , and the pulse peak voltage was 45 kV. The gas velocity was 1 ms^{-1} .	83
4.4 The particle reduction efficiency with various dust loadings. The supplied pulse peak voltage and the pulse frequency were 45 kV and 20 Hz, respectively. The gas flow velocity was controlled at approximately 1 ms^{-1} .	84
4.5 The particle reduction efficiency with various gas flow velocities. The supplied pulse peak voltage and the pulse frequency were 45 kV and 20 kHz, respectively. The dust loading was controlled at approximately 5×10^5 particles cm^{-3} .	85

LIST OF FIGURES

Figure		Page
1.1	Schematic diagram of the clean wind tunnel for ESP particle size efficiency test	4
1.2	Schematic of ESP electrode arrangements (GND: grounded electrodes)	5
1.3	Schematic diagram of the experimental setup used to measure particle capture efficiency of ESP with and without X-ray irradiation	6
1.4	Schematic diagram of experimental setup for performance electrostatic precipitator	7
1.5	A laboratory-scale pulsed ESP with wire-plate electrode configuration for experimental investigation on charging characteristics and penetration efficiency of PM _{2.5} emitted from coal combustion enhanced by positive corona pulsed ESP	8
1.6	Experimental set up for studied the separation characteristics of sub-micron particles in ESP with alternating electric field corona charger	9
1.7	The basic structure of a new-type ESP) designed by T. Watanabe <i>et al.</i>	10
1.8	Agglomerator test system. An aerosol generator, high voltage source and pump are shown to the left. The measurement system, shown on the right, consist of a Differential Mobility Particle Sizer(DMPS),electrical low-pressure impactor (ELPI) and Berner-type low-pressure impactor (BLPI)	11
1.9	The Schematic of experimental setup for agglomeration characteristics	13

1.10	Agglomerator test system. The aerosol generator, the high voltage source and the pump were on the left. The measurement system was on the right	14
1.11	The experimental apparatus of two-stage ESP with a bipolar charging	15
1.12	Side and front views of the pre-charger 1: insulator; 2: corona wire; 3: duct; 4: positive high-voltage connector; 5: negative high-voltage connector; 6: positive corona charger; 7: negative corona charger. The length of two identical wires was 1000 mm. The height and width of each corona charger were 150 mm, respectively	16
1.13	A pulse-energized electron reactor developed by J. S. Clements <i>et al.</i>	18
1.14	Schematic of new electric air cleaner system developed by M. Okubo <i>et al.</i>	19
1.15	Schematic of experimental setup for collection of submicron particles by an electrostatic precipitator using a dielectric barrier discharge	20
2.1	Schematic of corona discharge, particle charging and dust collection process in an ESP	23
2.2	A space charge field formed in the vicinity of the emitter electrode	25
2.3	The surrounding electric field lines of a) an uncharged particle and b) a charged particle surface area	27
2.4	Basic discharge modes in positive DC corona (a) glow mode (b) streamer mode	35
2.5	Streamer propagations with cathode and anode directed streamer	37
2.6	Plasma shielding on charged particle	39
2.7	Charging of dust particle in plasma field	40
2.8	Applied voltage and discharge current with time through the electrode gap	42

3.1	The wire-cylinder ESP configurations	45
3.2	The particle charge number on particle size ranged 0.10-1 μm at different electric field strengths	49
3.3	The migration velocity of fine particle in wire cylindrical ESP ($r_1 = 0.003\text{cm}$, $r_2 = 4.5\text{cm}$, $L = 50\text{cm}$, $U_g = 0.5\text{m/s}$)	51
3.4	Schematic diagrams of the experimental setup	55
3.5	The dimensions of the experimental ESP	55
3.6	Photograph of the experimental ESP	56
3.7	The circuit diagram of the pulse power supply	56
3.8	High voltage probe (Fluke model 80K-40)	57
3.9	True-RMS Digital Multi-meters (FLUKE 289)	57
3.10	High efficiency particulate-free air filter	58
3.11	A gas flow meter	58
3.12	A vacuum pump	59
3.13	A Digital Weighter Mettler Toledo model PB3002	59
3.14	Photograph of the particle counter (ParticleScan TM CR).	61
3.15	Voltage-current characteristics of the designed ESP for DC-energized and pulsed-energized	62
3.16	variation of the collection efficiency respect to pulse peak voltage with pulse frequency at gas velocity = 0.5 m/s	63
3.17	The size distribution of aerosol particle downstream of ESP operated at negative pulse voltage 10kV. The particle number concentration was measured at downstream of ESP with (On-control) and without the power supply (No-control), respectively. When the gas velocity was 0.5m/s	64
3.18	Variation of the fractional collection efficiency respect to respect to particles size (difference size rang 0.3 μm , 0.5 μm , 0.7 μm , 1 μm , 2 μm) for various pulse frequency when the negative pulse peak voltage, $V_p=10\text{kV}$, the particle number concentration, $N = 5 \times 10^5$ particles/ cm^3 , the gas velocity $u_g=0.5\text{m/s}$.	65

3.19	Variation of the fractional collection efficiency with respect to particles size (difference size rang 0.3 μ m, 0.5 μ m, 0.7 μ m, 1 μ m, 2 μ m) for various gas velocity when the negative pulse peak voltage, $V_p=10$ kV, The particle number concentration, $N =5 \times 10^5$ particles/cm ³ , pulse frequency, $f = 40$ kHz	66
3.20	Variation the fractional collection efficiency with respect to particles size(difference size rang 0.3 μ m, 0.5 μ m, 0.7 μ m, 1 μ m, 2 μ m) for various pulse peak voltage when pulse frequency, $f=20$ kHz, particle number concentration, $N =5 \times 10^5$ particles/cm ³ , gas velocity, $u_g=0.5$ m/s.	67
4.1	The experimental setup	75
4.2	The configuration of the ESP electrodes	75
4.3	Voltage-current characteristics of the ESP generators	78
4.4	(a) An electrical breakdown in a conventional DC ESP and (b) a plasma streamer in our pulse-excited ESP	79
4.5	Particle size distributions from the LPC (at the inlet).	79
4.6	Distributions of number of particles entering and leaving the Agglomerator when there is no electric field generation.at gas velocity 0.5 m/s and gas temperature 35 °C.	80
4.7	The submicron particle agglomeration in the test section.	81
4.8	The large particles that fell due to the agglomeration.	81
4.9	Agglomerations of submicron particles at different gas velocities.	86
5.1	The experimental setup	90
5.2	Variation of collection efficiency with air velocity at particle loading $> 5 \times 10^5$ particles cm ⁻³ , supplied voltages was 9 kV, when NTP pre-charger off and on mode.	92
5.3	Variation of overall collection efficiency with supplied voltage at particle loading 5×10^5 particles cm ⁻³ , gas flow velocity 1 ms ⁻¹ , when NTP pre-charger off and on mode	93
5.4	The overall collection efficiency with The overall collection efficiency with various gas velocity at difference dust loading and supplied voltages was 9 kV	94

NOMENCLATURE AND ABBREVIATIONS

Latin Symbols

Letter	Description	Unit
A	Surface area	[m ²]
A_c	Effective collecting area	[m ²]
C_c	Cunningham slip correction factor	-
D	Particle diffusion coefficient	[m ² /s]
De	Deutsch number	-
E	Electric field strength	[V/m]
E_c	Corona discharge onset field	[V/m]
E_o	Breakdown field	[V/m]
E_{ps}	Pseudo-homogeneous electric field	[V/m]
E_{ce}	Electric field near the collecting wall	[V/m]
F_D	Aerodynamic drag force	[N]
F_E	Electrostatic force	[N]
F_G	Gravitational force	[N]
I	Current	[A]
I_e	Electron current	[A]
I_i	Ion current	[A]
J	Net flux of particles	-
K_E	Translational kinetic energy	[N.m ² /C ²]
Kn	Knudsen number	-
L	Length of the tube	[m]
N_i	Ion concentration	[ions/m ³]
N_p	Particle number concentration	[particles/m ³]
N_s	Ion concentration above the surface	[ions/m ³]
N_m	Molecules concentration	-
P	Operating pressure	[Pa]
P_o	Reference pressure (1.013 × 10 ⁵ pa)	[Pa]
Q_g	Volumetric flow rate of gas	[l/min]
Re	Reynolds number	-
S	Sutherland constant	-
T	Absolute temperature	[K]
T_o	Reference temperature	[K]

Letter	Description	Unit
T_e	electron temperature	[K]
T_i	Ion temperature	[K]
U	Mean flow velocity	[m/s]
U_g	Gas velocity	[m/s]
U_m	Migration velocity	[m/s]
U_p	Particle velocity	[m/s]
V	Electric Potential	[V]
V_c	Corona discharge onset voltage	[V]
V_{diff}	Deposition velocity of particle diffusion	[m/s]
Z_i	Ion electrical mobility	[m ² /V.s]
$Z_{i,p}$	Ion electrical mobility at operating pressure	[m ² /V.s]
Z_p	Particle electrical mobility	[m ² /V.s]
Z_p	Particle radius	[m]
r_p	Mean thermal speed of ions	[m/s]
\bar{c}_i	Collision diameter of the particle	[m]
d_m	Particle diameter	[m]
d_p	Electron charge (1.6×10^{-19})	[C]
e	Pulse frequency	[Hz]
f	Current density	[A/m ²]
j_{ion}	Ion current density	[A/m ²]
k	Boltzmann's constant (1.38066×10^{-23})	[J/K]
m	Mass	[kg]
m_e	Electron mass	[kg]
m_i	Ion mass	-
m_p	Particle mass	-
n	Number of elementary charges	-
n_{diff}	Average charge number of diffusion charging	-
n_e	Number of electron	-
n_{field}	Average charge number of field charging	-
n_i	Number of ion charges	-
n_p	Number of elementary charges on the particle	-
n_s	Number of Saturation charge on the particle	-
r	Radial coordinate	[m]
r_c, r_1	Radius of corona wire	[m]
r_2	Radius of corona wire	[m]
t	Mean residence time	[s]

Letter	Description	Unit
t_d	Pulse duration time	[s]
t_s	Ion transit time	[s]

Greek Letters

Letter	Description	Unit
δ	Air density	[kg/m ³]
ε	Dielectric constant	[F/m]
ε_0	Electric permittivity of vacuum	[F/m]
η_t	Overall collection efficiency	-
η_f	Grade or fractional collection efficiency	-
η_r	Reduction efficiency	-
η_c	Overall collection efficiency	-
λ	Mean free path	[m]
λ_0	Reference mean free path	[m]
λ_D	Debye length	[m]
λ_{De}	Electron Debye length	[m]
μ	Gas Viscosity	[Pa.s]
μ_0	Reference Viscosity	[Pa.s]
ρ	Density	[kg/m ³]
ρ_p	Particle density	[kg/m ³]
σ	Standard deviation	-
σ_g	Geometric standard deviation	-
α	Townsend coefficient	-
α'	Net Townsend coefficient	-
β	Townsend coefficient	-

Abbreviations

Letter	Description
AC	Alternating Current
ADS	Anode Directed Streamer
BLPI	Berner-Type Low-Pressure Impactor
CDS	Cathode Directed Streamer
CNC	Condensation Nuclei Counter

Letter	Description
DBD	Dielectric Barrier Discharge
DC	Direct Current
DMPS	Differential Mobility Particle Sizer
DOP	Diocetyl Phthalate
DVM	Digital Voltmeter
EAA	Electrostatic Agglomeration Apparatus
ELPI	Low-Pressure Impactor
E/S	Electrospray
ESP	Electrostatic Precipitator
GMD	Geometric Mean Diameter
GSD	Geometric Standard Diameter
HEPA	High Efficiency Particulate Air
HV	High Voltage
NTP	Non-Thermal Plasma
PCD	Pulsed Corona Discharge
PDA	Doppler Anemometer
PM	Particular Matter
RF	Radio Frequency
RH	Relative Humidity
SMPS	Scanning Mobility Particle Sizer
UV	Ultraviolet