Fuzzy Logic Controller (FLC) for the Control of Particulate Matter (PM) Emission in Wet Scrubber System

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***Abstract*:** *Air pollution such as particulate matter (PM) emitted from industries result in several thousands of deaths. In recognition of this global threat, a large number of abatement measures have been taken to minimize the emission of this pollutant. Wet scrubber system has been the most widely used control device for PM contaminants. Its operating variables (gas velocity, temperature profile, particle size, liquid droplet's size, terminal settling velocity of liquid droplets, particle density and liquid to gas ratio) fluctuates randomly, thus resulting in a non-linear dynamic behavior of the system. This non-linearity generally limits the ability of the scrubber to control PM less than 5µm in diameter. Thus, in this study, intelligent control technique based on fuzzy logic controller (FLC) has been developed to solve the non-linearity in the system by selecting appropriate scrubbing liquid droplet size in order to improve system performance to control PM that are less than 5µm in diameter. The developed FLC has two inputs (error and change in error) and a single output. The results shows that within short settling time, the controller was able to effectively reduce the PM that are less than 5µm below the set-point (20µg/m^3) which is the maximum allowable emission limit of PM contaminants by world health organization (WHO).*

Keywords: *Air pollution, particulate matter, wet scrubber system, control, fuzzy logic controller*

1. Introduction

Air pollution is a serious threat to human health today. Air pollution is the presence of particulates, biological molecules, or other harmful materials in the Earth's atmosphere, possibly causing diseases, death to humans and damage to other living organisms [1]. Studies revealed that around 7 million people dies annually (one in eight of total global deaths) as a result of air pollution [2]. These findings shows that air pollution is now the world's largest single environmental health risk. Reducing air pollution could therefore save millions of lives.

According to [3], the two major air pollutants are particulate matter (PM) and ozone mostly emitted from industrial waste which result to several thousands of death. The Baseline Scenario's report shows that, even in 2020, significant risks to human health will remain from PM and ozone exposures if further stringent measures are not being taken [4]. Particles less than 100µm in diameter are termed as PM among which, particulates in the range 2.5µm -10µm and 0.1µm -2.5µm in diameter (known as PM_{10} and $PM_{2.5}$ respectively) are considered to be highly dangerous [5]. Studies revealed that, PM_{10} portion amounted to more than 90% and $PM_{2.5}$ portion are between 50% and 90% of the total PM emission [6]. $PM_{2.5}$ and PM_{10} are associated with a range of cardiovascular and respiratory diseases [7], and also difficult to control [8]. In recognition of these global threats, a large number of abatement measures have been taken to minimize the effect of these pollutants.

Wet scrubbers, dry scrubbers, electrostatic precipitators, fabric filters (backhouse) and cyclone separators are some of the most used air pollution control devices [9]. Wet scrubbers are effective at both PM and gas pollutants, and are also economically viable and simple than other particle control devices, hence they are used in small and medium scale industries for scrubbing particulate and gaseous pollutants [10-12]. Wet scrubbers are classified into spray towers, cyclone spray towers, tray towers, venturi scrubbers, orifice scrubbers, condensation scrubbers packed towers and dynamic scrubbers. In addition, spray towers are further classified into counter-flow or vertical spray tower, cross-flow or horizontal spray tower and co-flow spray towers. The main difference between these types of wet scrubbers is how the scrubbing liquid comes into contact with the contaminants.

In vertical spray tower type of wet scrubber systems, impaction mechanism is used in which the liquid droplet are introduced into the spray chamber to counteract with the PM contaminants. The thin film liquid droplet from spray nozzle provides a blanketing effect to entrap particles contaminants. A cylindrical spray chamber is considered for this research in which the gas phase (PM) is flowing upwards and a scrubbing liquid phase (water droplet) is flowing downwards as shown in Fig. 1. The ability of the system to remove particles depends on its operating variables [13].

Attempts have been made to improve the performance of wet scrubber system for the effective control of PM_{10} and $PM_{2.5}$ such as in [5, 8, 14, 15]. The operating variables of wet scrubber system (gas velocity, temperature profile, particle size, liquid droplet's size, terminal settling velocity of liquid droplets, particle density and liquid to gas ratio) lead to non-linear dynamic behavior for the scrubber system, hence making the system difficult to control using a conventional control technique. [16] proposed an intelligent control technique to predict the performance of wet scrubber system and [17] presented an approach to control PM contaminants that are less than 5μm in diameter. However, only one parameter (particle size) is considered as a disturbance variable which limits the control performance of the system when other parameters such as the gas velocity or gas temperature changes.

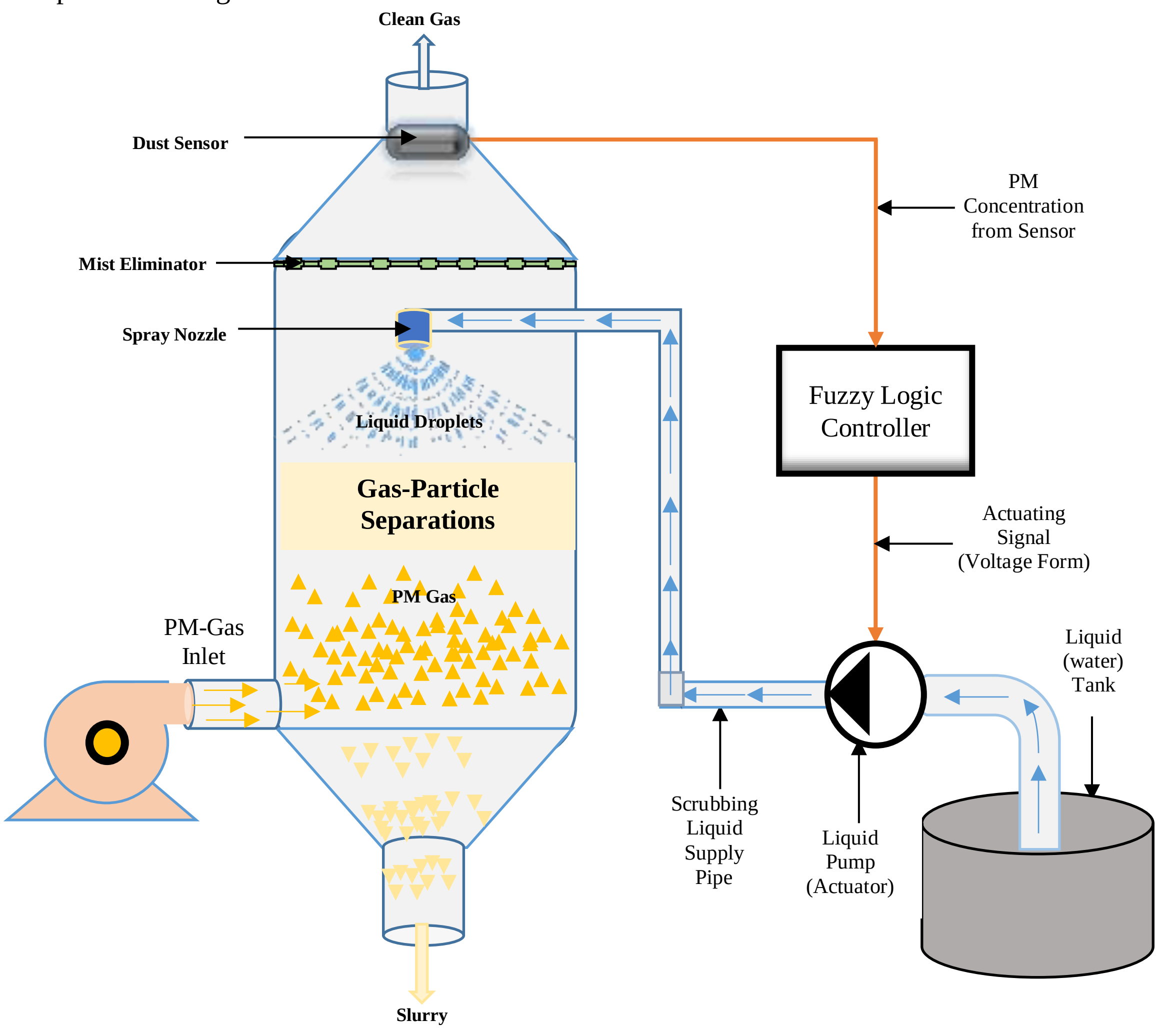

Fig. 1: Schematic Diagram of Proposed Spray Tower Wet Scrubber System for Gas-Particle Separations

Thus, in this study, intelligent control technique based on FLC is used to solve the non-linearity in wet scrubber systems by manipulating the scrubbing liquid (water droplet size) for the control of PM_{10} and $PM_{2.5}$. The controller has two inputs, error (difference between the set point and the actual PM concentration measured), change in error (difference between current and previous error) and a single output (change in droplet size). The droplet size changes based on the output concentration or the particle size. Smaller droplets size are needed to scrub smaller PM size.

The rest of the paper is organized as follows. The mathematical model of the system is presented in section 2, while the fuzzy logic controller design is given in section 3. Section 4 presents the results and discussions and section 5 concludes the paper.

2. Mathematical Model of the System

The main aim of mathematical model is to investigate the dynamic behavior of the system and implement the model using simulations. Meanwhile, mathematical modelling helps researcher to develop better understanding of the process and provides a significant potential for solving operational problems.

The mathematical model of vertical spray tower wet scrubber system used in [13, 16] were adopted for this research. The equations describing the performance efficiency of the scrubber system and PM concentration at the exit of the scrubber (1) and (2) respectively are the two fundamental equations used in describing the system.

$$\eta_{perf} = 1 - y_d / y_p = 1 - \exp\{-(3/2)(Q_L / Q_G) v_r /(v_r - v_g) z / d_D \eta_{sep}\} \quad (1)$$

$$y_d = y_p \exp\{-(3/2)(Q_L / Q_G) v_r /(v_r - v_g) z / d_D \eta_{sep} \quad (2)$$

where y_p is the PM concentration at the scrubber inlet (µg/m^3), Q_L / Q_G is the liquid to gas ratio, v_r is the relative velocity (m/s), v_g is the gas velocity (m/s), z is the height of the scrubber (m), d_D is the droplet diameter (m), and η_{sep} is the gas-particle separation efficiency.

The separation efficiency is an important factor that describes the system performance and it depends upon three mechanisms; impaction, interception and diffusion [16]. For the impaction mechanism, the separation efficiency is given by equation (3).

$$\eta_{sep} = \{\psi /(\psi + 0.35)\}^2 \quad (3)$$

where ψ is the impaction parameter which is the determining factor for particle separation due to impaction mechanism. The larger the value of the impaction parameter, the higher the separation efficiency [13]. The impaction parameter has a model as indicated in (4).

$$\psi = c_{cf} \rho_p (v_{td} + v_g) p_D^2 / 18 \mu_g d_D \quad (4)$$

where c_{cf} is the Cunningham slip-correction factor, μ_g (5) is the gas viscosity (kg/m s), v_{td} is the terminal settling velocity of liquid droplets (m/s), ρ_p is the particle density (kg/m^3) and p_D is the particle diameter (m).

The Cunningham slip-correction factor (6), is considered as a safety parameter [16], it allows for the prediction of drag force on a particle moving within a fluid.

$$\mu_g = 0.0234 + 0.0001464(T + 273) \quad (5)$$

$$c_{cf} = 1 + Kn[1.257 + 0.4\exp(-1.1/ Kn)] \quad (6)$$

where Kn is the Knudsen number given by (7)

$$Kn = 2\lambda / p_D \quad (7)$$

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λ is the gas mean free path (m) given by (8)

$$\lambda = \mu_g / 0.998\sqrt{(2\rho_g / \pi)} \quad (8)$$

From (8), ρ_g is the gas density in (kg/m^3) given by (9)

$$\rho_g = PM_g / R(T + 273) \quad (9)$$

T is the gas temperature (^{o}C), P is the atmospheric pressure (1atm), M_g is the molecular weight of the gas (29g) [16], and R is the universal gas constant (8.31448J/mol K).

The terminal settling velocity of liquid droplets is given by (10).

$$v_{td} = \sqrt{(4/3)gd_D(\rho_D - \rho_g)/C_D\rho_g} \quad (10)$$

From (10), g is the gravitational acceleration (m/s^2), and C_D is the drag coefficient (11), which is a function of Reynolds number (12) of the liquid droplet.

$$C_D = 24f / \mathrm{Re} \quad (11)$$

$$\mathrm{Re} = \rho_g d_D(v_{td} - v_g)/\mu_g \quad (12)$$

$$f = \begin{cases} 1 + .0916\,\mathrm{Re}, & for\, 0.1 \le \mathrm{Re} \le 5 \\ 1 + 0.1588\,\mathrm{Re}, & for\, 5 \le \mathrm{Re} \le 10^3 \\ 1.34 + 3/\sqrt{\mathrm{Re}}, & for\, \mathrm{Re} \le 10^5 \end{cases} \quad (13)$$

3. Fuzzy Logic Controller Design

Fuzzy logic is a powerful problem solving technique with a myriad of applications in control systems. It provides an easier way to draw definite conclusions from uncertain, ambiguous or imprecise information [18]. Fuzzy logic is similar to human decision making because it has the ability to incorporate the expert experience of a human operator in the design of the controller for controlling a process whose input – output relationship is described by collection of fuzzy control rules (IF-THEN rules) involving linguistic variables [19]. The fuzzy logic controller used in this study has a basic architecture as shown in Fig. 2.

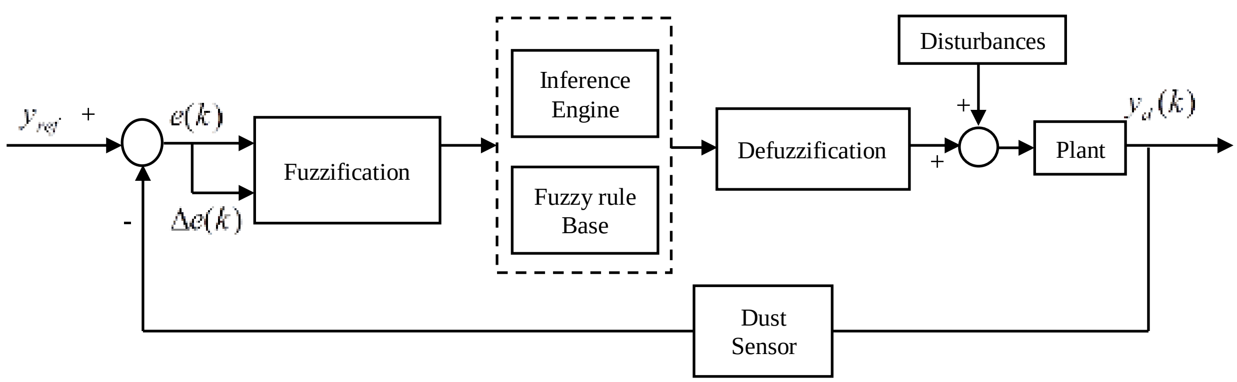

Fig. 2: Basic Architecture of the Proposed Fuzzy Logic Controller

The inputs to the controller used for this design are error and change in error and the output is change in output (change in droplet size) as given in equation (14), (15) and (16) respectively.

$$e(k) = y_{ref} - y_d(k) \tag{14}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{15}$$

$$\Delta d_D(k) = d_D(k) - d_D(k-1) \tag{16}$$

The following steps are considered in developing the controller:

- **Step 1: Fuzzification of the Input Variables**

Fuzzification is a process of mapping from an observed input space to fuzzy sets in a certain input value limited to the universe of discourse, μ= [-1, 1]. A membership function (MF) is assigned to each fuzzy input and output. The MFs used for each input and output are negative big, negative small, zero, positive small and positive big

- **Step 2: Inference Mechanism**

The process of fuzzy inference involves all the membership functions, fuzzy logic operators and IF–THEN rules. A Mamdani-type fuzzy model is used which is the default, AND fuzzy operator was used to generate the rules with equal weight.

- **Step 3: Fuzzy Rule Base**

Fuzzy rules are represented by a sequence of linguistic statements of the form IF THEN, leading to algorithms describing what action or output should be taken in terms of the currently observed information. The rules are generated as shown in Table I. Each of the two inputs and output has five membership functions which results to twenty five distinct rules.

TABLE I: FLC Rule Generation Algorithm

		Δe(k)			
e(k)	**NB**	**NS**	**ZO**	**PS**	**PB**
NB	PB	PB	PB	PS	ZO
NS	PB	PS	PS	ZO	NS
ZO	PS	ZO	ZO	ZO	NS
PS	PS	ZO	NS	NS	NB
PB	ZO	NS	NB	NB	NB

KEY: NB=negative big, NS=negative small, ZO=zero, PS=positive small, PB=positive big

- **Step 4: Defuzzification**

Defuzzification convert the fuzzy output (linguistic variable) back to the crisp variable or classical output to the control objective. The default type, centre of area was used in converting the linguistic variable back to the crisp.

The PM size to be control fall between the range 0.1 µm -10µm ($PM_{2.5}$ and PM_{10}). The corresponding PM concentration for ammonium nitrate were given by [9], as shown in Table II. The liquid droplet size, d_D has been adopted from Hago nozzle Sauter mean diameter [17], and the size ranges between 19.50µm – 54.0µm.

TABLE II: Mass PM Size and Concentration for Ammonium Nitrate

No	Particle Size(µm)	Concentration(µg/m^3)
1	19.93	9,681,000.587
2	7.53	4,644,000.666
3	4.90	244,000.229
4	3.78	176,000.619
5	2.23	67,000.312
6	1.26	47,000.803
7	0.75	19,000.955
8	0.37	9,000.829

4. Results and Discussion

Fig. 3a shows output response of the developed fuzzy logic controller. Since the value of the PM concentration is very high, such that the relationship between the PM concentrations at the scrubber output (y_d), the manipulated variable (d_D), the disturbance variables (d_P and T) and the set point (y_{ref}) are not clearly shown in the diagram. Hence, the PM concentration axis is scaled down for clear view as shown in Fig. 3b.

Two types of disturbances (changes in particle size and changes in temperature profile of the gas) are considered. The particles size changes randomly between 0.1µm to 20µm while the gas temperature was initially maintained at room temperature of 25°C for simulation time of 60 seconds and later changed to 35°C to indicate a disturbance. Despite the presence of these disturbances, the controller was able to efficiently maintain the output concentration below the reference value within a short settling time by appropriately changing the droplet size.

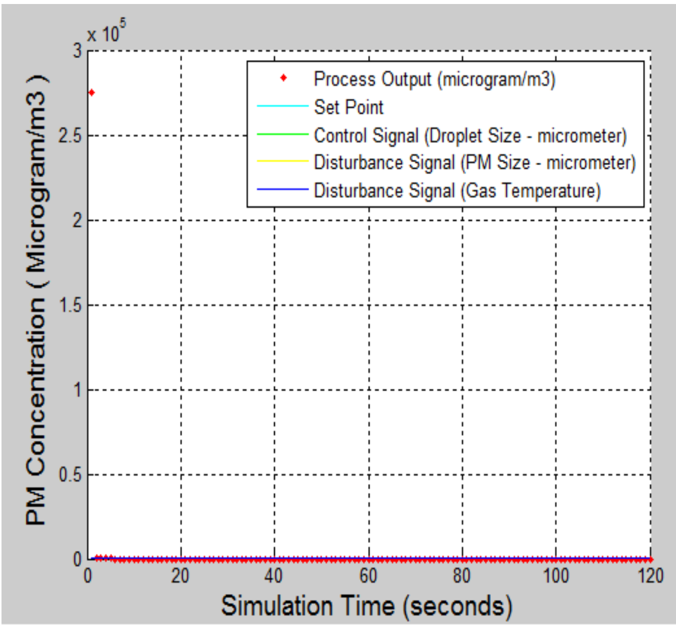

Fig. 3a: FLC Response

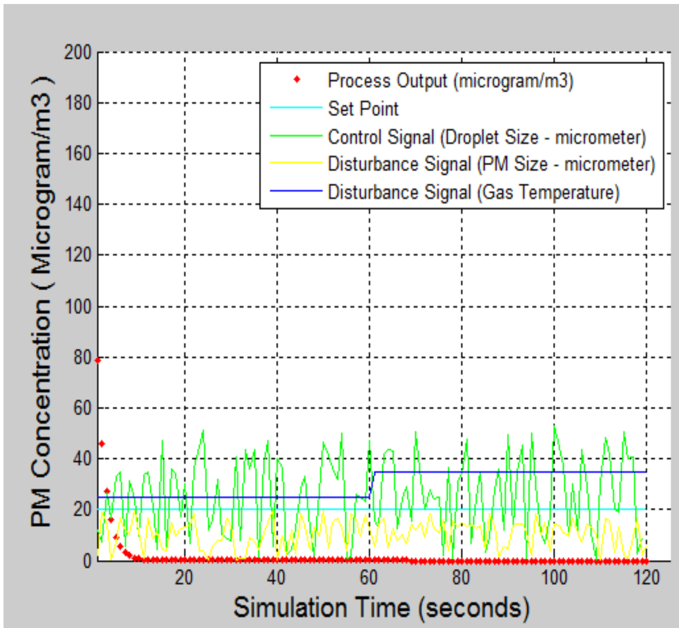

Fig. 3b: FLC Response

5. Conclusion

In this paper, intelligent control technique based on fuzzy logic controller (FLC) has been developed to control the emission of PM contaminants (PM_{10} and $PM_{2.5}$) below the set point of 20µg/m^3, which is the maximum allowable emission limit of PM by world health organization (WHO). Smaller scrubbing liquid droplet sizes are needed to control smaller sizes of PM contaminants. The scrubbing liquid provides a blanketing effect to entrap particles contaminants. The controller select appropriate liquid droplets size to scrub the PM contaminants. The result shows that the controller was able to efficiently manipulate the scrubbing liquid droplets size to maintain the PM concentration below the set point within a short settling time.

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