CHARACTERIZATION OF THERMAL PRECIPITATOR IN SMOKE COLLECTOR BY USING PARTICLE COUNTER

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First Registered on November 30th 2012; Received after Corection on April 18th 2012
Publication Approval on : April 30th 2012

ABSTRACT

Air pollution in major cities in many countries has reaching a very concerning level. One of the cause of air pollution is pollution caused by smoke aerosol. Smoke aerosols that has an average particle diameter of 0.1 μm – 1 μm can be found in cigarette smoke, diesel vehicle fume, industrial fume and many else. This condition will be worsen by the increase in the number of smokers, motor vehicles and industry. Therefore we need to pursue the control method for that kind of air pollution. In the literature study, it's found that the cleaning method of air filtration for fine particle with dimension of 0.01 – 5 μm are by using thermal precipitator. Thermal precipitator is one method of air filtration based on thermophoretic force, which is if there is a temperature difference between two plates, it will cause the force that will push the particles between the two plates toward the plate that has lower temperature. In the effort to help control and reduce the air pollution, for this study we made a thermal precipitator test equipment to deposit the particles in the air with the use of thermophoretic force. That force is the force applied to the particles that suspended in the fluid flow. The temperature difference between two plates is set at ΔT*=5, 10, 15, and 20*^{o}*C. This study utilized gas sensors to observe the characterization of thermal precipitator. From the experiment and analysis can be concluded that thermal precipitator can be applied as a smoke collector.*

Keywords: *thermal precipitator, smoke collector, gas sensor*

I. INTRODUCTION

Air pollution in major cities in many countries has reaching a very concerning level. This condition is also happened in Indonesia, particularly in the capital city of Jakarta, which became a barometer for other cities in Indonesia, has reached a concerning level so it caused the drop in air quality and environmental support capacity. Smoke aerosol is one of the air pollution. Smoke aerosol with submicron-micron sized particle (0.01 – 5 μm) are often found in cigarette smoke, diesel vehicle fumes, industrial fumes and many others. Efforts to control air pollution are limited in the form of pamphlets, banners, etc. Even if there are rules that provide sanction to air pollution, but the implementation in the field is not optimum.

Thermophoresis plays an important role in the mechanism of movement of submicron-sized particle in the aerosol technology. Thermophoresis phenomenon describes the movement of particle caused by temperature difference around the particle. If there is any temperature difference around the particle between two regions (e.g plate), it will cause the force and the particle between two plates will move toward the plate that has lower temperature. This thermophoresis effect was first studied by

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Tyndal in 1870 and later by Aitken in 1884. They clarified, that particles must be driven away from hot surface. This occurs due to a net force, acting in the opposite direction to the gradient temperature, toward the low-temperature region and is a direct result of the differential bombardment of the gas molecules that comes from the relatively hot and relatively cold regions in the vicinity of the particles. A phenomenon referred now to as thermophoresis. Deposit that accumulated in heat exchanger equipments is caused by thermophoresis, studied by Nishio *et al*. Byres *et al.* and Romay *et al*.

Standford Research Institute (Figure 1) in 1961 stated that the cleaning method for particle with dimension of 0.01 – 5 μm are by using thermal precipitation – particle separation by using heat. Thermophoresis in a laminar tube flow has been studied thoroughly. Stratmann *et al.* (1989) experimentally studied thermophoretic deposition using 0.005 – 0.1 μm monodisperse aerosol in a laminar tube flow. Montassier *et al.* (1990) carried out experiment with an experimental set-up that was similar to that employed by Stratmann *et al.* except for the direction of the flow and the measuring technique. A. Messerer, *et al.* in 2003 using thermophoresis to deposit soot aerosol particles in the exhaust system of diesel engine. Byung Uk Lee, *et al.* in 2006 conducted a similar study to A Messerer and stated that thermophoresis is a dominant factor to deposit the particle with 0.02 – 0.05 μm of size in the vehicle exhaust system. Later in 2008 Zhou Tao *et al.* conduct an experiment to visually prove that thermophoresis has a great influence to make a 1 – 30 μm particle deposit, but a little for the particle larger than 30 μm. Earlier in 2004, Gallis M.A., *et al. thermophoresis* force can be used as *thermal precipitator* that can be applied more broadly in life, especially for pollution control. The same thing was observed by Gonzales D. *et al.* in 2005. K.K. Dinesh *et al.* studied the thermophoretic deposition in natural convection flow through a parallel plate channel with heat sources. Effect of thermophoresis particle deposition from a horizontal flat plate embedded in a porous medium was studied by Adrian Postelnicu (2007). Not only experimentally, thermophoresis in annular flow theoretically studied by D.P. Healy *et al.* in 2010.

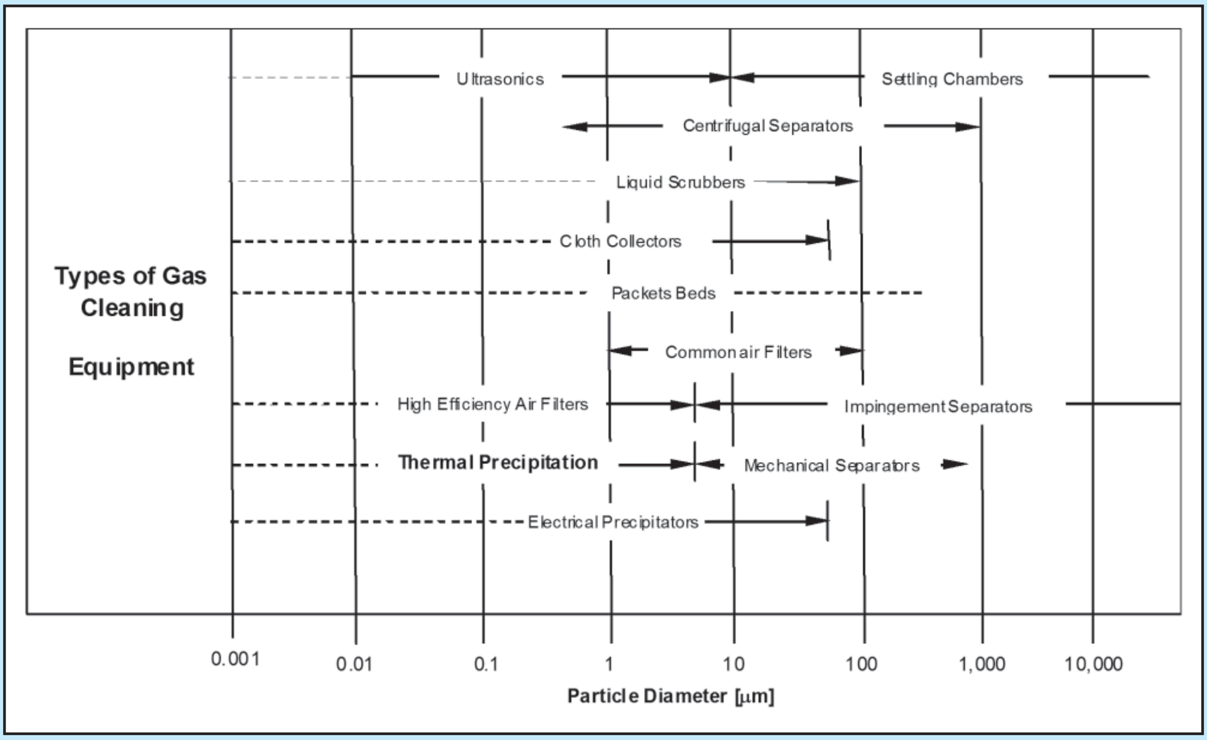

Figure 1
Particle size and character

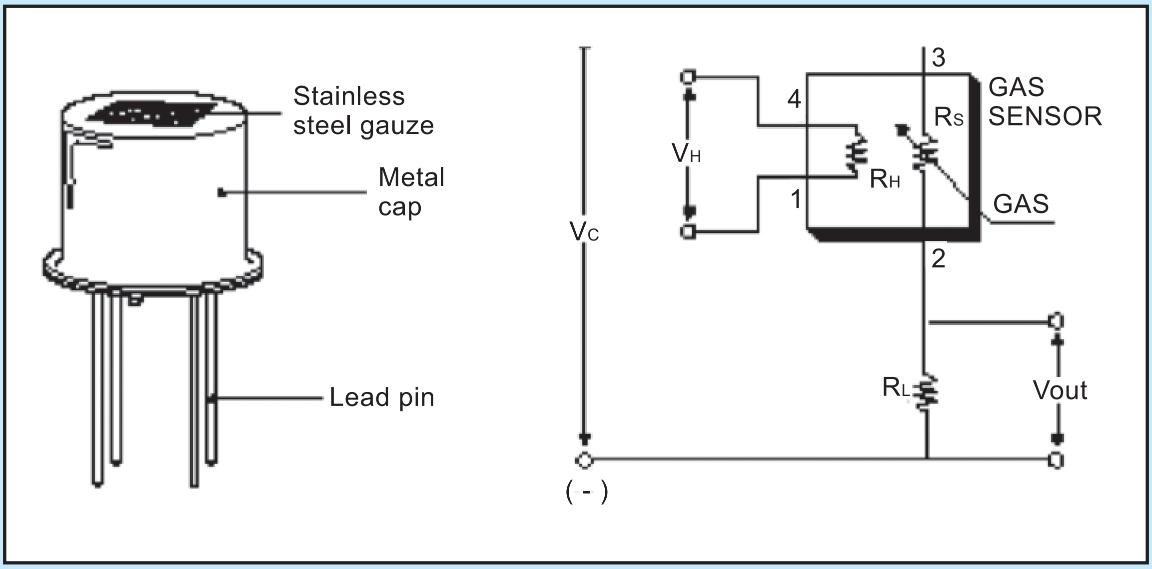

Figure 2
Gas sensor figaro 2600

Deposit of fine particle is not only influenced by thermophoresis. Chi-Chang Wang studied a combined effects of inertia and thermophoresis on particle deposition onto a wafer with wavy surface. Other researchers like Iman Zahmatkesh clarified that, deposition particle ~ 100 µm mainly occurs by inertial impaction. Thermophoresis is the dominant deposition mechanism for particles ~ 10 µm. Brownian diffusion contribute on the deposition of 10 nm. On the another hand, Changfu You studied the effect of electrostatic field and thermophoresis on inhalable particulate matter. Effect of thermophoresis and electrophoresis on particle deposition onto a vertical flat plate was studied by R. Tsai *et al.*

Many research about thermophoresis has been conducted and it is said that thermophoresis is the driving force for the deposit accumulation. But, research regarding thermal precipitator is rare. Therefore the smoke collector device has been conducted. That is the reason why we are conducting this research by conducting experimental study of thermal precipitator test equipment to deposit the particles in the air by utilizing thermophoretic force. Therefore, first thing to do is by investigating and characterizing the thermal precipitator itself.

II. THEORY

Thermophoresis force was studied by M. Eipstein in 2005 by assuming spherical particle and the fluid is ideal gas, stated that thermophoretic force:

$$Fx = \frac{6\pi.Dp.\mu^2Cs.(K + Ct.Kn)}{\rho(1 + 3Cm.Kn)(1 + 2K + 2Ct.Kn)}\frac{1}{T}\frac{\delta T}{\delta x} \quad ..(1)$$

Where Fx is Thermophoresis force, Kn is Knudsen number = $2\lambda/Dp$, λ is particle distance, K = k/kp, where k is fluid thermal conductivity, k = (15/4) µR, kp = particle thermal conductivity, Cs = 1,17; Ct = 2,18; Cm = 1,14, T = local fluid temperature, µ = fluid viscosity.

In this paper, an experimental study was conducted. the particle concentration or smoke deposited on the plate was measured by using gas sensor and particle counter. The type of the gas sensor is Figaro TGS 2600 (Figure 2). It is designed to measure concentration of pollution that prevalent in the room such as cigarette smoke. This sensor is commonly used to detect the presence of gas. This gas sensor can be applied as an alarm and also to measure gas concentration depends on the microcontroller circuit that is used. This gas sensor consist of a resistance value (Rs) that will respond when exposed to gas and has a heater that is used to clean sensor in internal chamber from air contamination from the outside.

Output voltage signed at the resistor RL (Vout) is used as an input to microprocessor. The material of gas sensor is metal oxide, particularly SnO_2

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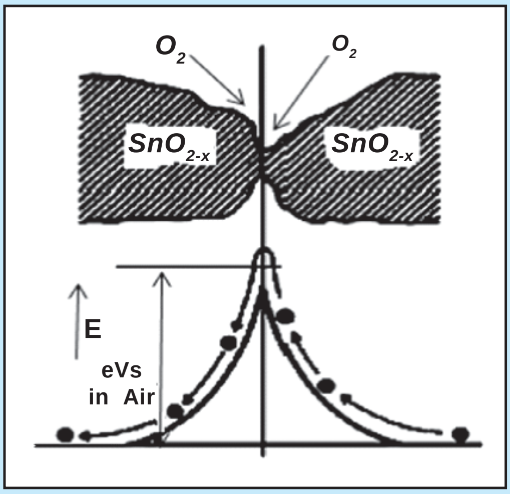

Figure 3
Illustration of oxygen absorbtion by the sensor

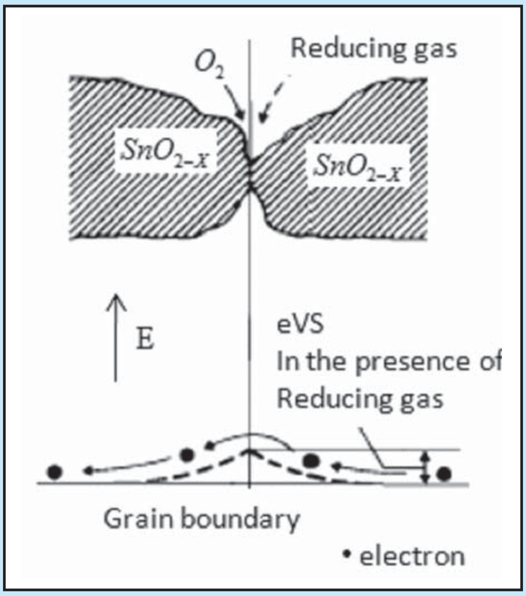

Figure 4
Illustration when Gas is Detected

compound. In Figure 3 and Figure 4 are shown the illustration of Oxygen absorbtion by the gas sensor, when crystal metal oxide (SnO_2) is warmed at given temperature, oxygen will be absorbed in the crystal surface and oxygen will be negatively charged. The absorbed oxygen by the sensor can be seen from the following chemical equation:

Figure 5
Gas sensor and microcontroller

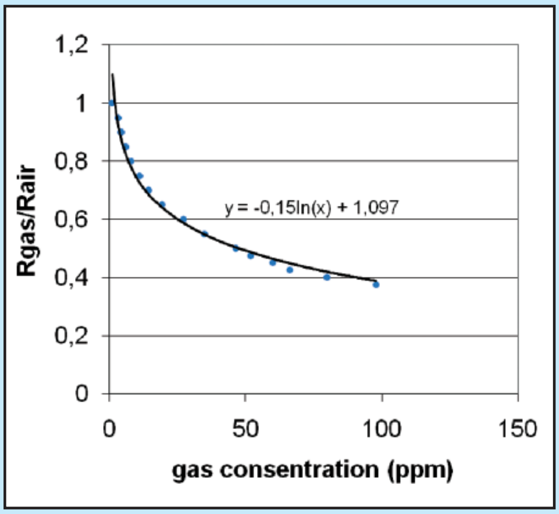

Figure 6
Graph showing the relationship between R_{gas}/R_{air} vs consentration

$$1/2O_2 + (SnO_2)^* \rightarrow O^- ad(SnO_2$$

This will occur because the crystal surface donate electrons to the oxygen contained in outer layer, so that the oxygen will be negatively charged and positive charge will be formed on the outer surface of the crystal. Formed surface tension will inhibit the rate of electron flow.

In the sensor, current flows through the junction area (grain boundary) of SnO_2 crystal. At the junction, oxygen absorption prevents the charge to move freely. If the gas concentration decreases, deoxidation process will occur, surface density of negatively charged oxygen will be reduced, and resulting in the decreasing of the barriers height in the junction area. If there is presence of CO gas that is detected, then chemical equation as follow.

$$CO + O^{-}ad(SnO_{2-X}) \rightarrow CO_2 + (SnO_{2-x})^{*}$$

Obtained value from the gas sensor are still in the form of voltage ratio (R_{gas}/R_{air}), then to get the number of particle, R_{gas}/R_{air} value must be converted to ppm (part per million) by using graph as shown in Figure 6.

The signal data from the sensor will be sent to the microcontroller which is then displayed to the LCD screen in digital form. The picture of the gas sensor system and the microcontroller can be seen in Figure 5.

Clean room standard issued by US FED STD 209E and ISO 14644-1 FED STD 209E are using particle/m^3 or particle/ft^3 as the unit. Therefore the data to particle/m^3 or particle/ft^3 were converted using particle counter P-TRACK 8525. P-TRACK 8525 that have the following specification: concentration range: 0-5x10^5 particles/cm^3, particle size range : 0.02 – 2.5 µm, operation temperature range : 0 – 38 ^{o}C, and level of accuracy: 0.01%. Calibration process from the gas sensor to the particle counter were done in same condition at the time of experimentation. The graph in Figure 7 shows the result of the calibration. From the calibration we obtain the following equation:

$y = -(3e+7)x^3 + (7e+7)x^2 - (6e+7)x + (2e+7)$ ... (2)

with a deviation $R^2 = 0.994$.

III. EXPERIMENTAL SETUP

Particle used in this study is cigarette smoke type with the specifications as shown in Table 1.

In general, as shown in Figure 8, the experimental apparatus consist of a inlet and outlet smoke container box, test section is equipped by a heater in order to keep the hot side of the plate and cooling water to keep the cold side of the plate, gas sensor TGS 2600, microcontroller, and LCD display. Cigarette smoke is stored in the container box made of acrylic, and at this position one gas sensor is placed to measure the smoke density in the air. Through the inlet section, smoke flows to the test section consists of 2 stainless steel plate. One of the plate is attached to a heater in order to maintain the temperature on the hot side. To have the variation of the temperature on the hot side, voltage regulator is applied. The test plate section dimension is 15 cm x 50 cm and distance between two plates is 5 mm. To measure the air velocity, we use a hot wire anemometer. The average air velocity in the test section is 5 cm/s. To maintain the temperature of the cold side of the plate stable, cooling water is flowed into the plate. Temperature is maintained at 26.85^{0}C. Then smoke will be deposited in the cold side of the plate so the level of the smoke that coming out from test section

Table 1
Test particle specification

No	Parameter	Value	Unit
1	Aerosol type	Smoke	
2	Aerosol name		
3	Particle diameter	0.01 ~ 1	µm
4	Density	1.1	g/cm^3
5	Molecular mass	162.23	g/mol
6	Boiling point	247	^{o}C

Ref.: British American Tobacco (www.bat-science.com)

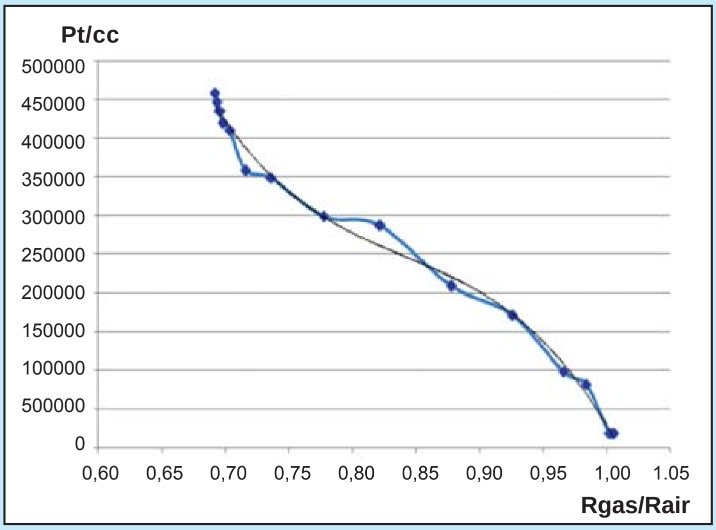

Figure 7
Particle calibration to pt/cc

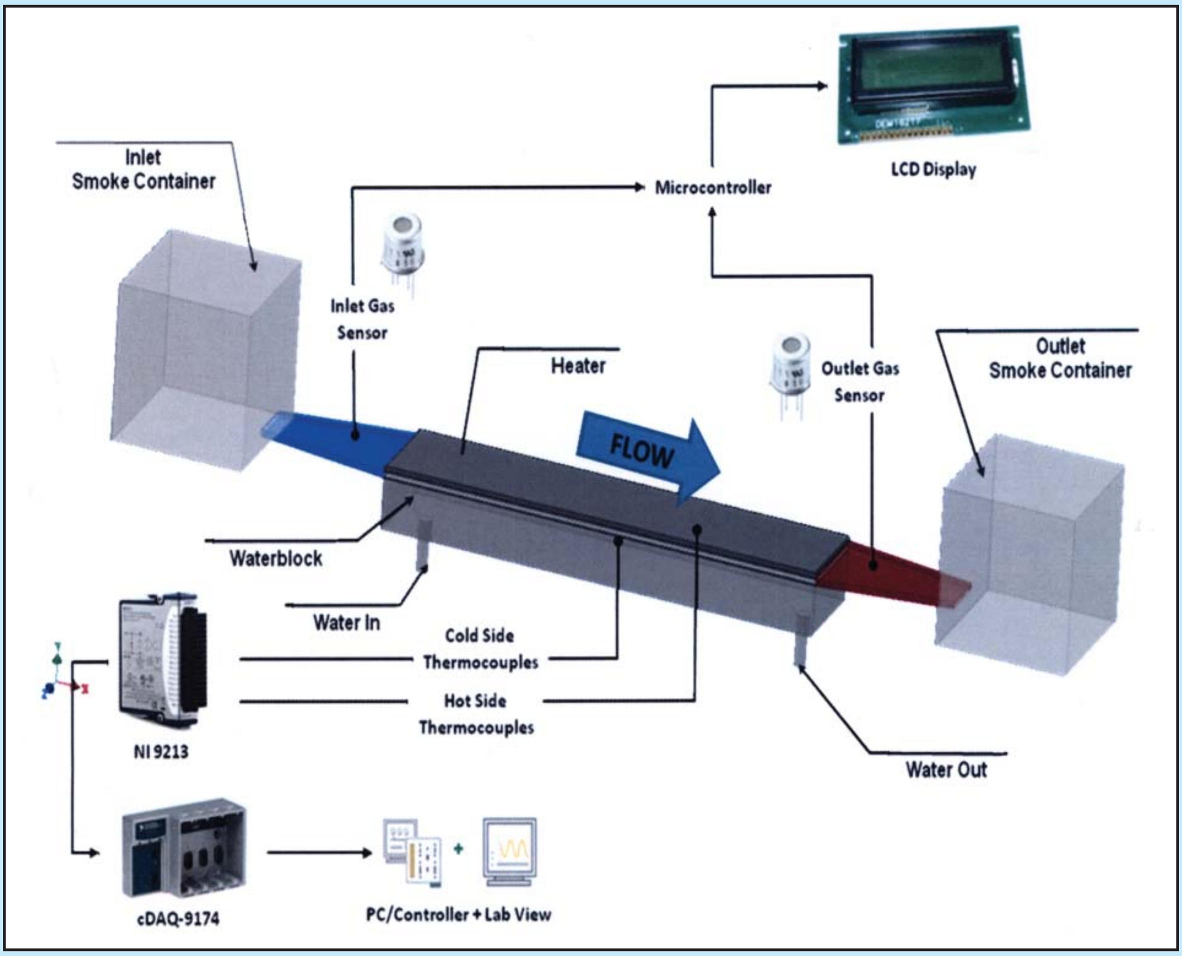

Figure 8
Testing scheme

through gas sensor that placed in the outlet section can easily be known. Data received by the gas sensor was sent to the microcontroller then displayed t in the LCD screen in digital form. 7 pieces of gas sensor (G1 – G7) is mounted in the test section as shown in Figure 9.

The variation of temperature difference (ΔT) between hot plate and cold plate are set as follow: 0^o, 5^o, 10^o, 15^o, and 20^{o}C. But to avoid the misinterpretation of temperature difference (ΔT) in thermophoresis for example if hot plate temperature (T_2) = 50^{o}C and cold plate temperature (T_1) = 27^{o}C, then ΔT will be $\Delta T = T_2 - T_1$ = 23^{o}C. This ΔT = 23^{o}C can also be

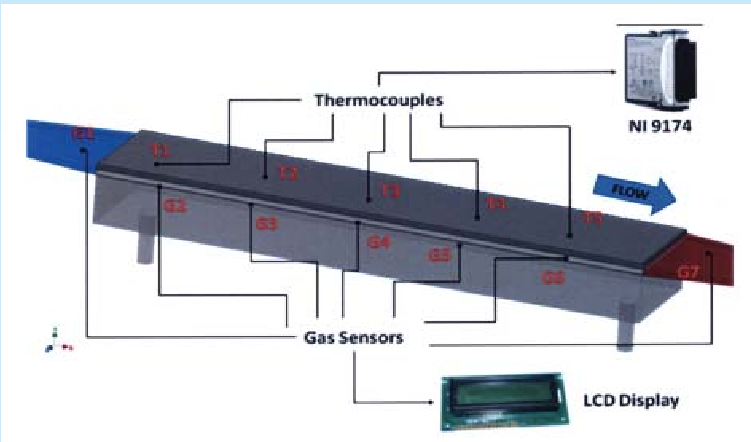

Figure 9
Test section

interpreted T_2 = 100°C and T_1 = 77°C, where both of them have a different radiation and convection effect. Therefore we create new non-dimensional parameter for temperature, namely T*. Where $T^* = (T_{hot} - T_{cold})/T_{hot}$ or $T^* = (T_2 - T_1)/T_2$. Temperature is measured using Type-K thermocouple and data collection was carried out using a data acquisition system (NI cDAQ-9174). In this research 5 (T1 – T5) thermocouples type-K were used and mounted on the surface of the plate as shown in Figure 9. Photo of the experiment equipment can be seen in Figure 10.

To clarify the effect of gravity on this research, the position of hot plate are arranged so that may be positioned above and below. Other factors affecting the particle movement will be discussed in the result and discussion.

IV. RESULT AND DISCUSSION

Data from testing results can be seen in Table 2., while the test graph can be seen in Figure 11- 15.

Figure 11 shows the graph of the test result for ΔT = 0°C or T* = 0 when the heater is not operated so the test equipment works in the ambient temperature. The average number of particle in the inlet section is 14,160 pt/cc and in the outlet section is 13,328 pt/cc, so the average difference is 833 pt/cc. It means that the deposited particles are very small, so it can be said that the thermophoretic force did not occur,

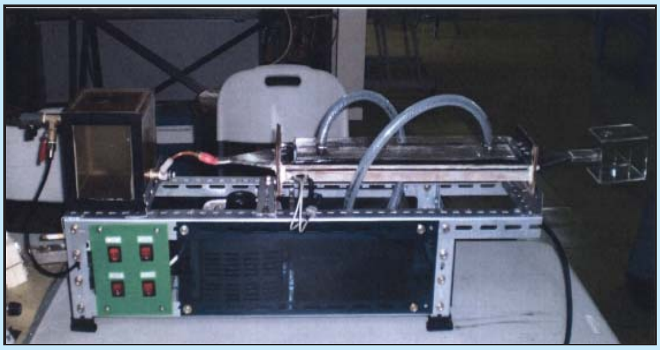

Figure 10
Thermal precipitator test equipment

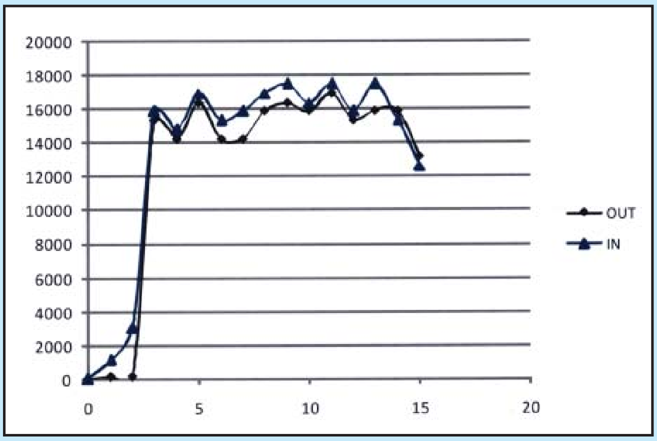

Figure 11
Deposited particles at T*=0

Table 2
The number of deposited particle

ΔT	0		5		10		15		20	
Thot	25		30		35		40		45	
Tcold	25		25		25		25		25	
T*	0,00		0,17		0,29		0,38		0,44	
	IN (pt/cc)	OUT (pt/cc)	IN (pt/cc)	OUT (pt/cc)	IN (pt/cc)	OUT (pt/cc)	IN (pt/cc)	OUT (pt/cc)	IN (pt/cc)	OUT (pt/cc)
	14.160,99	13.328,08	15.536,47	6.524,99	15.954,46	6.974,51	16.092,46	6.795,21	16.922,06	13.084,78
Deposited Particle	832		9011		8979		9297		3837	

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its mean no deposited particles.

The graph in Figure 12 shows the number of particle when entering and exiting the test section for the temperature difference between hot plate and cold plate at 5°C or T* = 0.17. In the first 5 seconds, the effect of thermophoresis is cannot be observed yet but in the next second and so on, there is a very significance difference in the particle number. The average number of particles in the inlet is 15,536 pt/cc (particles per cubic centimeter) and in the outlet is 6,524 pt/cc, so the average difference is 9,011 pt/cc. This amount is the particle that deposited on the cold side of the test section. The similar result was obtained if the cold side of the test section in placed on the top. This means there is no gravity that influences the particle. So, how about the influence of buoyancy force, Shafmann lift force, Brownion motion and electrostatic force, will be described below.

Bouyancy force arises because of the viscosity difference in a fluid. In a gaseous fluid, viscosity will decreases with increasing temperature. The influence of buoyancy force in a fluid can be known from the heat transfer mechanism experienced by the fluid. Bouyancy force only appears on the convection that occurs naturally. To determine the type of convection that occurs, we can compare its Grasshoff value and Reynolds square value (Gr/Re^2) of the fluid. In this experiment, the comparison between Grasshoff value and Rayleigh square is so small, so the Bouyancy force can be ignored.

Saffmann lift force is a lift force on a particle caused by the friction between particle and fluid flow. Due to extremely fine particle diameter, the particle will be lifted against the force of gravity. In this experiment, the air velocity is very low at 5 cm/s, therefore the Shafmann lift force can be ignored and if Shafmann lift force does exist, it would be very little.

According to Brownion motion, this motion occurs in submicron-sized particle ($d < 0.01\mu m$), because of the inter-particle momentum. Brownion motion is a random motion of suspended solid particle in a fluid. Brownian motion occur when an imbalance force that generated from the movement of

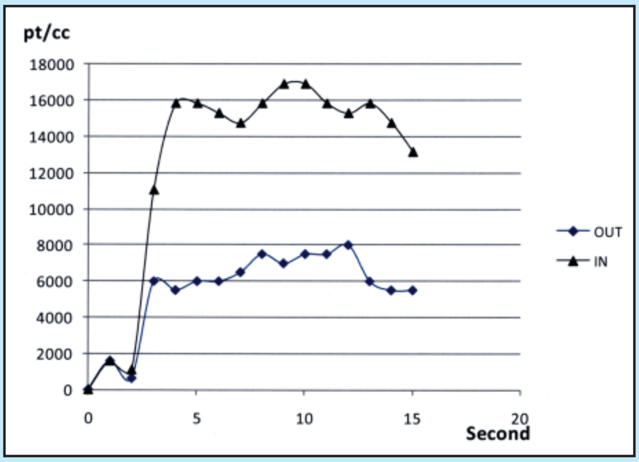

Figure 12
Deposited Particles at T* = 0,17

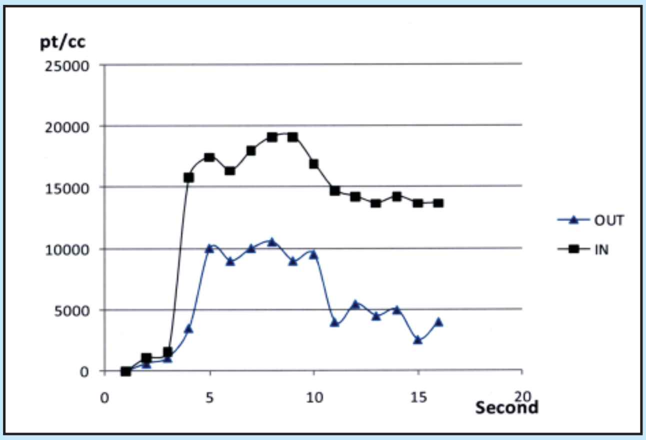

Figure 13
Deposited Particles at T*=0.29

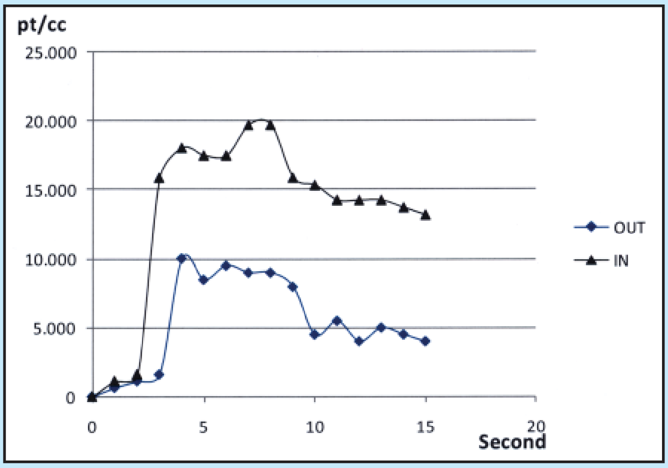

Figure 14
Deposited Particles at T*=0.38

fluid particles that are much smaller than the solid particle and impacted the solid particle repeatedly. Due to very small dimension of the particle, therefore to be able to produce Brownian motion, solid particle dimension must be very small. Brownion motion applies to the sub-micron particle in laminar flow. In this study, the particle that used is the smoke with size large than 0.01 µm, so that the influence of Brownion motion can be ignored.

The influence of electrostatic force do not exist because this force happened if there is the difference in inter-particle electrical charge. This force occurs in a particle if the particle is placed in electrical field which has voltage difference of E = 10^4 V. Based on Changfu You et.al (2010), electrostatic force will be effective and have a big impact for the particle size larger than 10 µm. While the smoke particle only have the size up to 2.5 µm.

The Graph in Figure 13 shows the number of particles when entering and exiting the test section for temperature difference between hot plate and cold plate at 10°C or T* = 0.29. In the first 3 seconds the effect of thermophoresis is cannot be observed yet but after 5 second, there is a very significance difference in the particle number. The average number of particles in the inlet is 15,954 pt/cc and in the outlet is 6,974 pt/cc, so the average difference is 8,979 pt/cc.

Similar thing also happened in the graph in Figure 14 for temperature difference between hot plate and cold plate at 15°C or T* = 0.38. Themophoretic force can be observed after 3 seconds. This is indeed happened because the distance between test section and inlet section is 15 cm and the air velocity is 5 cm/s. The average number of particle in the inlet section is 16,092 pt/cc, while in the outlet section is 6,795 pt/cc, so the average difference is 9,297 pt/cc.

If we see the average difference of the particle, for ΔT 5°C, 10°C and 15°C, they tend to have similar thermophoretic capabilities. The average number of particle that deposited is 9000 pt/cc. If we refer the clean room standard, ISO 14644-1 FED STD 209E, This equipment is not yet meet the standard when operated at ΔT 15°C.

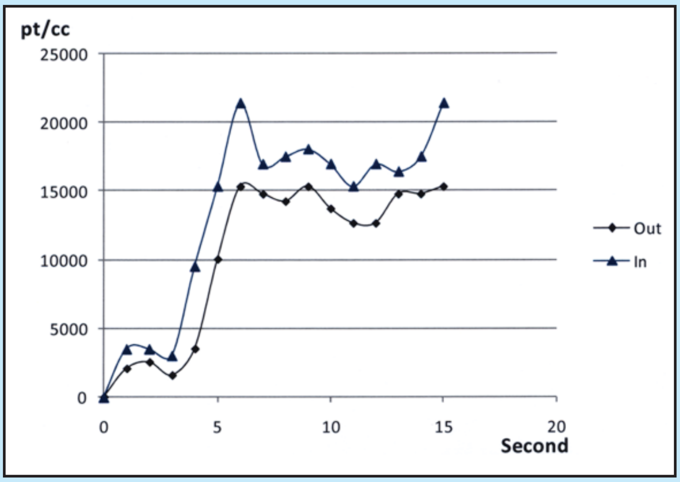

Figure 15
Deposited particle at T*=0.44

A rather odd thing happed at ΔT = 20°C or T* = 0.44. As shown in Table 2. and graph in Figure 15, average number of particle in the inlet is 16,922 pt/cc and the outlet is 13,084 pt/cc, so the average number of particle is 3,837 pt/cc. This is occurs because the influence of convection on the hot plate, so the thermal boundary layer that is former is greater than the distance between two plates (larger than 5mm).

V. CONCLUSION

The characterization of thermal precipitator as an alternative device for smoke collector has been conducted. The particle that is used as sample is a cigarette smoke. Their diameter range of 0.01 – 1 µm. The average number of particle in the inlet section is 16,000 pt/cc and in the outlet section is 7,000 pt/cc, then the average number of deposited particle is 9,000 pt/cc. We can conclude that thermophoresis is the driving force for the accumulation of the deposit or it may be said that the thermal precipitator is potential to be used as smoke particle collector with average efficiency of 56%. Thermal precipitator can be used as particle collector device like diesel vehicle fume and industrial fume. If we look at the range of particle diameter that can be collected, this thermal precipitator has a potential to be applied as an aerosol collector.

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