The Development of High Temperature Recirculating Pump (HTRP) for Energy Savings in an Incinerator

N. A. H. Mohamed[1], R. Zakaria[1*], M. N. M. Yunus[2]

[1]School of Chemical Engineering, Universiti Sains Malaysia
Seri Ampangan, 14300, Nibong Tebal, Pulau Pinang.
[2]Malaysia Institute for Nuclear Technology Research, Bangi, 43000 Kajang, Selangor.
**Email:* chduan@eng.usm.my

ABSTRACT

Tremendous increase ingeneration of Municipal Solid Waste (MSW) has become a major concern for the Malaysian government as the country experiencing rapid development. It was estimated about 16000 tones/day MSW is produced at national level and in Kuala Lumpur alone about 2500 tones/day. Annually, it was predicted to rise about 2%. Incineration, being one of the Integrated Waste Management Solution (IWMS) was found to be a best option to overcome the waste management problem; it is proven by the number of incinerators available in developed country such as Japan, which exceeding 1000 units. This is clearly confirmed, that incineration has become one of the best option because it gives volume and weigh reduction of the MSW by 83% and 91% respectively. Currently, an incineration pilot plant called Thermal Oxidation Plant (TOP) has been installed in Malaysia Institute for Nuclear Technology Research (MINT) and it is experiencing delay in ram up time in primary chamber which has results more auxiliary fuel from design value is being consumed before the chamber reach the combustion temperature. The presence of high moisture level (60%) was found to be a reason of this phenomenon. Therefore, a High Temperature Recirculating Pump (HTRP) has been developed to overcome this problem and therefore some energy saving could be realized through flue gas recirculation method in an incinerator. The experimental results of HTRP from cold fluid and hot fluid tests have confirmed the potential of application of HTRP as a recirculation engine to overcome the current problem. Integration of these results into starved air incinerator model has result in reduction of auxiliary fuel consumption in primary chamber up to 25.91 %.

Keywords: Municipal Solid Waste, Incineration, High Temperature Recirculating Pump.

1. INTRODUCTION

Incinerator which carries out burning activity results from the rapid oxidation of substances has the same meaning as combustion. Combustion however is generally used more often in the area of fossil fuel burning for steam or power generation and incineration is used more often when referring to waste combustion (Lee et al., 1989). Principally, any types of starved air incinerator consist of two combustion chambers, which referred as primary and secondary chamber. The current practice of incinerating MSW using starved air incinerator involved the use of primary chamber to partly gasify the solid waste, followed by burning the gaseous product in a secondary chamber. The primary chamber is ignited by a primary burner, and typical to Malaysian waste having up to 60% moisture (Yunus et al., 2001), a substantial amount of fuel is needed to dry out the moisture from this waste in the primary chamber prior to combustion. For environmental reason and typical to the starved air incinerator, secondary chamber temperature is needed to sustain at above 850°C even from starting or as soon as the combustion in primary chamber started. As the first 4 hours is almost needed for drying process, not much combustible volatiles of significant calorific value will be generated in the primary chamber during this phase. Currently, typical to the plant in MINT, there is no heat recovery involved, thus all heat generated is released into the environment. It is envisaged that, if part of the heat generated in the secondary chamber could be reused or recycled into the primary chamber, some form of energy saving could be realized.

Therefore, to solve this problem, a High Temperature Recirculating Pump (HTRP) has been designed to recirculate some part of combustion products (flue gases) that have been generated in the secondary chamber back to primary chamber. Flue gas recirculation methods have been studied in various research institutions to treat the flue gases and to control formation of NO_x in combustion chamber of incinerator, boiler and turbines. Godridge (Priestman and Tippetts, 1995) reviewed much work on flue-gas recirculation (FGR) in a study of oil-fired plant. The conventional method of external recirculation relies on mechanical means and typically consists of up to 30% of flue gas being cooled prior to being pump back into system by fan. The disadvantage of the fan-recirculation system is the need to cool the flue gas and the possibility of fan failure (Priestman and Tippetts, 1995).

This recirculating device was developed based on jet pump concept and it was named High Temperature Recirculating Pump (HTRP) due to its function to entrain hot flue gases. HTRP has potential to suit many applications in various fields and it is simple in term of operations. The jet-pumps were developed in the nineteenth century to maintain vacuum pressures in the condenser of steam engines (Eames, 2002) and the absence of moving parts attract researchers to maximize its potentials. This pump has wide range of applications, among which refrigeration that has long-establish history and solar-powered refrigeration system (Wu et al., 1995). Tremendous developments have been made on applications of jet-pump in field of nuclear engineering and aerospace industries.

The HTRP has been subjected to two different test namely, cold fluid test and hot fluid test. The results obtained from the experiments were used to calculate the flue gas recirculation process. However, the working principle is not discussed here.

2. INCINERATION PROCESS

Incineration of MSW generally involves three basic processes: drying, pyrolysis which takes place at absence of air and gasification in primary chamber and followed by complete combustions in secondary chamber. The primary chamber operates at 450°C and secondary chamber sustain above 1000°C with residence time 2 seconds and Figure 1 shows a schematic diagram of starved air incinerator with flue gas recirculation engine (HTRP).

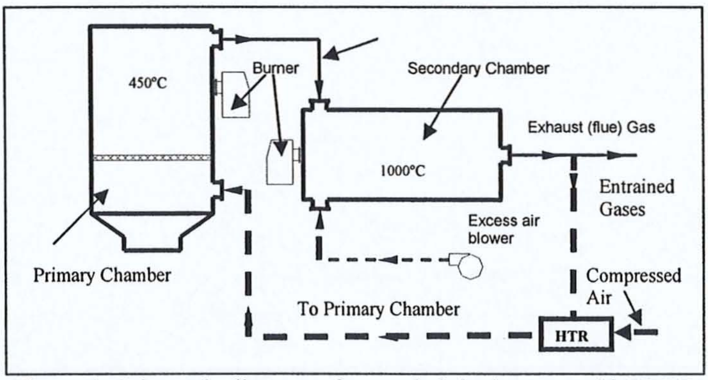

Figure 1: Schematic diagram of starved air incinerator with HTRP

The energy saving through HTRP design was obtained by incorporating experimental results from hot fluid test and cold fluid test into starved air incinerator model which was developed based on work conducted by Yunus (1991). The model was developed using spreadsheet to represent starved air incinerator to combust MSW as described in Figure 1 along with flue gas recirculation engine (HTRP). The primary chamber has been set to operate at sub-stoichiometric condition so that the gasification process can take place. Since the gasification process took place in the primary chamber, the formations of CO gases are maximum and to create this condition, the total air input to the chamber must be $X \leq X_{CO\ max}$. The general mass balance equation (1) for gasification process in primary chamber is as follows:

$$C_xH_yZ_z + XM_S(3.76N_2 + O_2) \rightarrow n_1CO_2 + n_2H_2O + n_3CO + n_4CH_4 + n_5N_2 \quad (1)$$

Where,

x = Mass of Carbon / Atomic weight of Carbon
y = Mass of Hydrogen / Atomic weight of Hydrogen
z = Mass of Oxygen / Atomic weight of Oxygen
X = Total amount of air, Ms = Stoichiometric air

Auxiliary fuel is needed in the system to sustain the chamber temperature and play very important roles in early stage of combustions due to low calorific values of MSW. The fuel (CH_4) having calorific value of 55,880 kJ/kg and the chemical reaction of fuel which principally methane is shown bellow:

$$n_6CH_4 + M_F(O_2 + 3.67N_2) \rightarrow n_7CO_2 + n_8H_2O + n_9N_2 \tag{2}$$

Energy balance for primary chamber calculated by applying equation (3).The total energy input to the system is sum of energy contain within the waste and the energy delivered by the burner after reaching flame temperature which equivalent to operating temperature. The total input energy is deducted with energy needed to vaporise the amount of water or moisture presence in the waste. The total amount of energy output is the sum of energy from the volatile products of combustions and enthalpies of the product gases. The heat losses in the process are assumed as a 5% through the shell and 0.25% through ashes (5).

$$Q_{in} = \mathrm{m}_{\mathrm{waste}}CV_{waste} + m_{air}Cp_{air}T_{in} - [m_{moisture}(h_l + h_s] + m_{fuel}CV_{fuel} \tag{3}$$

$$Q_{out} = \sum m_{volatile}CV_{volatile} + \sum m_{product}Cp_{product}T_{exit} \tag{4}$$

$$Losses = Q_{in}(5.25\%) \tag{5}$$

Combustion products from primary chamber will go to secondary chamber and will be combusted completely to form carbon dioxide and water. The overall air supply to primary and secondary chamber is 2.0 (X_t) of the stoichiometric air needed (Ms). The mass balance equation (6) for combustion in secondary chamber is as follows:

$$n_{10}CO + n_{11}CH_4 + X_SM_S(O_2 + 3.76N_2) \rightarrow n_{12}CO_2 + n_{13}H_2O + n_{14}N_2 + n_{15}O_2 \tag{6}$$

Energy balance calculation in secondary chamber is similar to the method applied in the primary chamber.

3. HIGH TEMPERATURE RECIRCULATING PUMP (HTRP)

Flue gas recirculation (FGR) is a method of entraining combustion products in the form of gases which possess high energy at extreme temperature from secondary chamber and delivered back to primary chamber. In order to recycle the product gases, a device that can work at high temperature environment is required. Therefore, a HTRP has been designed and tested. The mass and energy balance for HTRP is explained below:

3.1 MASS BALANCE

Mass Balance for HTRP is;

$$m_1 + m_2 = m_3 \tag{7}$$

$$m_1 + (R_m)m_1 = m_3 \tag{8}$$

Where the subscripts 1, 2 and 3 represents the mass flow rate of motive fluid, the entrained fluid and the total fluid at the outlet of HTRP respectively.

3.2 ENERGY BALANCE
Energy Balance for HTRP is;

$$Q_1 + Q_2 = Q_3 \tag{9}$$

$$m_{air} Cp_{air} T_o + (R_m) m_{air} Cp_{products} T_{Secondary\ exit} = \Delta H = Q_3 \tag{10}$$

The subscript 0 in motive fluid represent standard temperature if the driving fluid is not preheated.

4. RESULTS AND DISCUSSION

4.1 COLD FLUID TEST

Cold fluid test involves the experiments on HTRP at ambient conditions. Here, the HTRP has been tested with various size of driving nozzle which was characterized by area ratio (ϕ) and the result is shown in Figure 2. Area ratio (ϕ) is a ratio between cross sectional area of driving nozzle (A_{nozzle}) to cross sectional area of mixing throat (A_{throat}) in the HTRP. The performance of HTRP is characterized by entrainment ratio (R_m) which is defined in the following manner m_2 / m_1. The experiment was conducted by varying the motive or driving pressure from 151.98 kPa to 455.96 kPa (absolute pressure) for fixed size of nozzle (ϕ).

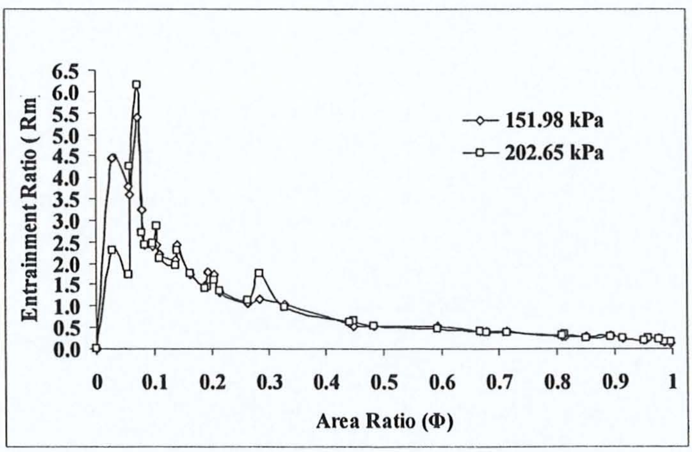

Figure 2: Experimental results from cold fluid test

The graph shows that at constant driving pressure, for an example, 151.98 kPa, the entrainment ratio (R_m) increases as the nozzle size or area ratio reduces (ϕ). At higher driving pressure (202.65 kPa), more entrainment take place. The highest entrainment ratio (R_m) of 5.38 and 6.16 was documented at area ratio (ϕ) of 0.071 for 151.98 kPa and 202.65 kPa driving pressure respectively. Overall it can be said that each area ratio (ϕ) behave uniquely according to the driving pressure. The result for greater driving pressure is shown in Figure 3. The fluctuation in the entrainment ratio (R_m) shown may be due to the recirculation effect in the mixing throat of HTRP and blockage effect.

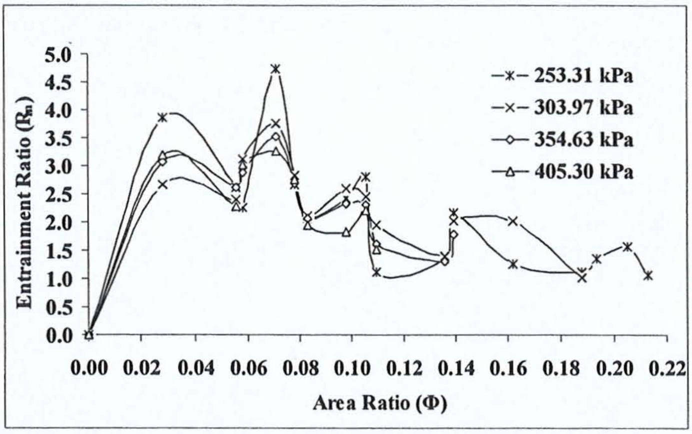

Figure 3: Entrainment ratio (R_m) at various driving pressure

4.2 HOT FLUID TEST

Similar to cold fluid test, the entrainment ratio (R_m) is a parameter, which has been studied to identify the potential of High Temperature Recirculating Pump (HTRP) during hot fluid test. Driving nozzle with area ratio (ϕ) of 0.0829 was tested in the hot temperature environment and the outcome of the experiment is shown Figure 4. The nozzle was subjected to test with driving pressure ranged from 151.98 kPa and 253.31 kPa. During the test, the highest temperature documented in the entrainment section of HTRP is about 480°C. For driving pressure 151.98 kPa, the initial entrainment value at temperature 39.4°C is about 2.67 and this increase as the operating temperature rise gradually to 450.30°C and results the entrainment ratio to 2.94, which amount to 10.11 per cent increments. The fluctuation in entrainment was observed due to the recirculation effect in the mixing throat. Generally it can be concluded that the entrainment ratio (R_m) increase linearly with temperature as shown in Figure 4. The thermal efficiency of HTRP was calculated by dividing the measured temperature at exit section of pump with input temperature at entrainment port and from the experiment, the calculated average thermal efficiency of HTRP is about 62 %. From here, it could be deduced that if we want the exit temperature to be about 500°C, the entrainment temperature shall be at least 500 °C /0.62 = 806.45 °C. Therefore it can be concluded that the HTRP was successfully tested working at high temperature environment.

4.3 ENERGY SAVINGS

By incorporating the results obtained from cold fluid test and hot fluid test of HTRP into the starved air incinerator model, the energy saving in primary chamber can be predicted. The developed model is capable of predicting theoretically the amount of auxiliary fuel required to perform partial combustion in primary chamber and followed with complete combustion in secondary chamber. For a 1000 kg of MSW having characteristic as in Table 1, the required amount of combustion air per hour for 12 hours operation cycles time when the primary chamber stoichiometric air ratio (X) was set to 0.3 is 83.5 kg/h. For this, the suitable driving nozzle size in term of area ratio (ϕ) is 0.0978 which has taken from combination of Nozzle-80° and Spindle-30°. At driving pressure 303.97 kPa, the corresponding entrainment ratio (R_m) during cold run test is 2.59. Generally, it was found to increase 10% during hot run and its result to 2.85. Figure 5 shows some prediction of energy saving at various sub-stoichiometric air condition and pump application condition. When the model was tested without FGR for sub-stoichiometric air ratio (X) of 0.3, the calculated amount of auxiliary fuel consumption in primary chamber is about 85.06 kg, of which 33.3 kg of total fuel was consumed to evaporate the 60 percentage of moisture in the waste. With the incorporation of HTRP, the total auxiliary fuel consumption in primary chamber was reduced to 77.63 kg and this shows an energy saving of about 8.73 % in the primary chamber. The amount energy being saved when the primary chamber operated at sub-stoichiometric air ratio of 0.57

using two units of HTRP was about 25.91 % of the total auxiliary fuel consumption at 54.46 kg.

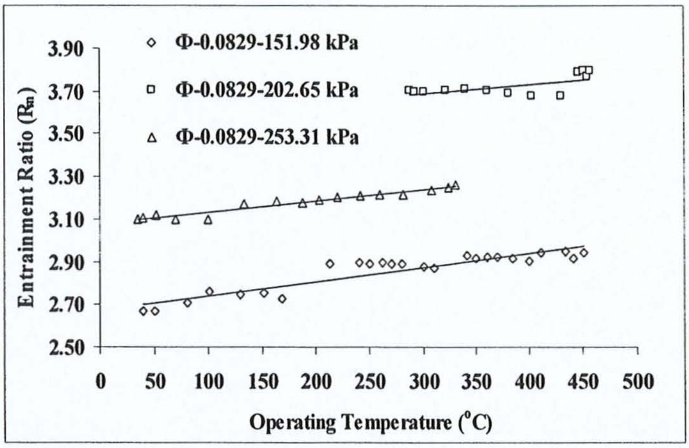

Figure 4: Changes of entrainment ratio respected to temperature rice at area ratio (ϕ) of 0.0829.

TABLE 1: Starved air incinerator's operating parameters (Kathiravale et al., 2002)

Sample : A	MSW weight :	1000 kg
Proximate analysis:	Moisture:	60 %
Ultimate analysis:	Carbon:	56.37 % (by weight)
	Hydrogen:	8.15 % (by weight)
	Oxygen:	40.16 % (by weight)
Lower heating value (LHV):	17,696.04 kJ/kg	
Primary chamber temperature :	450 °C	
Secondary chamber temperature :	1000 °C	
Combustion air :	The total air at both chambers was set to 2.0 time's stoichiometric air required.	

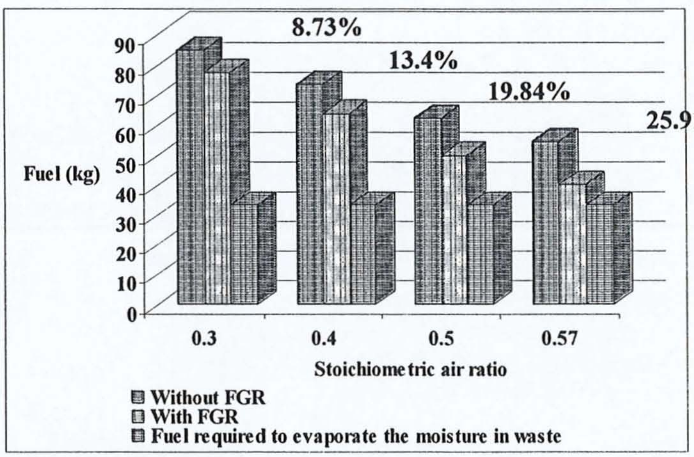

Figure 5: Fuel consumption in primary chamber for 1000 kg of MSW (LHV = 17, 696.04 kJ/kg) for characteristic was listed in Table 1.

5. CONCLUSION

Through this analysis, it can be concluded that the High Temperature Recirculating Pump (HTRP) is capable recirculate the hot flue gases generated in the secondary chamber back to the primary chamber and promote some energy savings through reduction in auxiliary fuel consumption.

ACKNOWLEDGEMENTS

The author would like to thank Malaysian Institute for Nuclear Technology Research (MINT) and Universiti Sains Malaysia (USM) Short Term Grant for the funds and facilities provided to conduct this research project.

REFERENCES

Eames, I. W. (2002). "A New Prescription for the Design of Supersonic Jet-pumps: The Constant Rate of Momentum Change Method". *Applied Thermal Engineering*, **22**, 121-131.

Kathiravale, S., Yunus, M.N.M., Samsuddin, A. H., Sopian, K. and Rahman, R. A. (2002). "Prediction of Municipal Solid Waste gasification Conditions Using A Simple Spreadsheet Based Model" : In: 6th Asia Pacific International Symposium on Combustion and Energy Utilisation , 20/22, 161-166.

Priestman,G. H. & Tippetts, J .R (1995). "The application of a variable-area jet pump to the external recirculation of hot flue-gases". *Journal of Institute of Energy*, **68**, 213-219.

Lee, C. C & Huffman, G. L, *Incineration of Solid Waste*. U.S. Environmental Protection Agency. U .S. Office of Research and Development: Cincinnati. EP.8.3.pp 143-151, (1989).

Yunus, M. N. M (1991). "Modelling and investigation of a clinical waste incinerator". Master thesis, University of Sheffield.

Yunus, M.N.M., Mohamed, Z & Kumar, R. (2000). "Progress in the Treatment of MSW in TOP". International Conference on Combustion, Incineration/Pyrolysis and Emission Control.

Sun, D. A and Eames, I. W (1995). "Recent development in the design theories and applications of ejectors-a review".*Journal of the Institute of Energy*.**68**, 65-79.

Exposure to radiochemical or radioactive materials such as radioisotope will cause great illness to operating personnel. To avoid from this situation, usually operating personnel draw the sample form special room or galleries, separated from the process areas by 4-6 ft of shielding. The sampling room are situated higher than the process areas to prevent drainage of process liquid through the sampling lines into the sampling galleries and to provide good drainage back into the process vessels between samplings. Usually, the sampling room is situated far from the process area where samples are drawn through lines that are very long relative to the volume of sample taken and sample supply line must be rinsed with many volumes of liquid in order that sample will be representative (9).

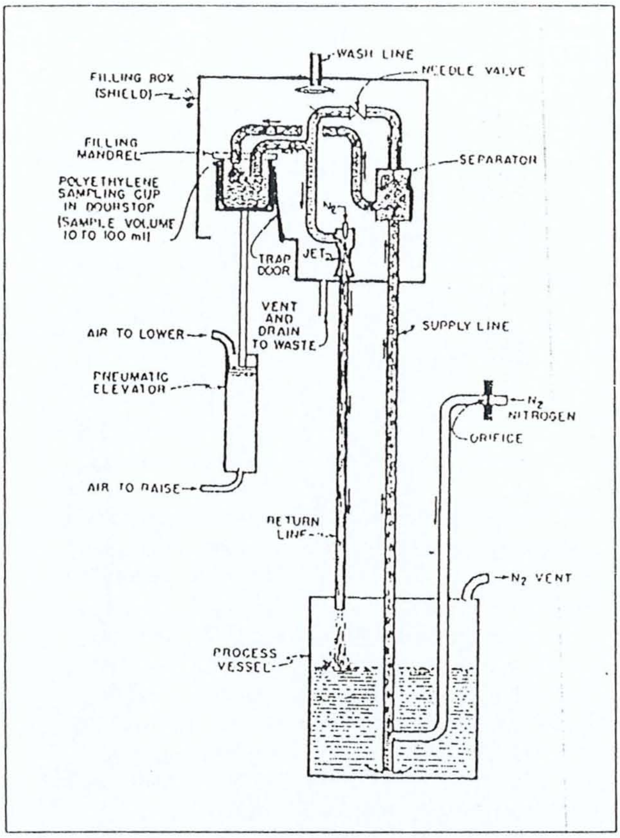

Figure 3: One type of sampler in use at radiochemical plant (9)

In the above diagram, the ejectors are positioned in two points. For both of the ejectors, nitrogen gas is used as motive fluid to entrain process liquid for purpose of sampling and returning the access liquid back to the processing vessel. A plastic sampling cup with the carrier is placed on the elevator and is raised through the trapdoor in the shielded filling box. A stream of liquid from the process vessel is drawn through the inlet line, separator, and sample cup by the action of the jet, which discharge the stream back to the vessel. The jet is aided by an air lift in supply line and nitrogen is used to operate the jet and air lift. The nitrogen bubbles from the air lift are removed at the separator. After representative sample has been obtained in the cup, the cup is lowered from the filling box, and capped and taken to the laboratory. As soon as the cup is lowered from the sampler lines drain back to the process vessel (9).

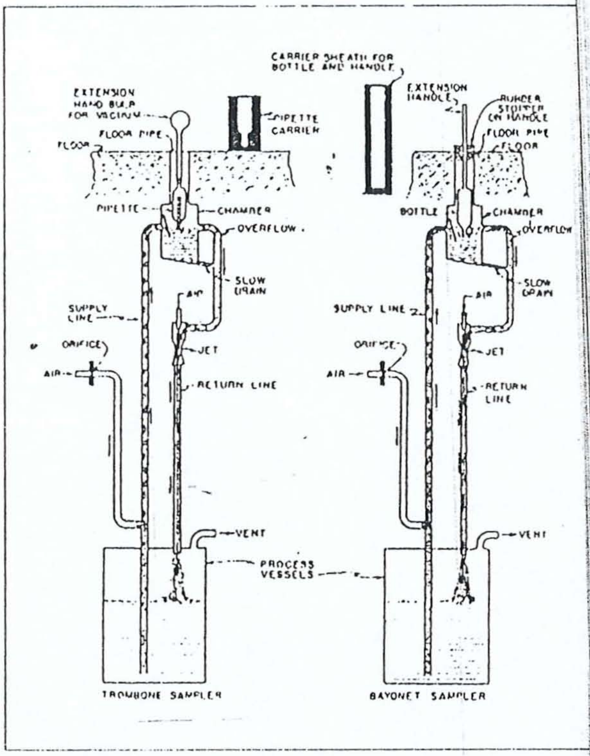

Figure 4: Trombone and Bayonet sampler (9)

The trombone and bayonet samplers are shown in Figure 4. These techniques are less radioactive which enable sampling about 0.5 to 5ml. Two ejectors have been placed in the system and air being used as motive fluid for sampling purposes. Process liquid is recirculated through a chamber shielded beneath the floor. In the trombone sampler, a pipette with a plastic well at the tip is lowered on an extension just within the chamber liquid. A hand operated – vacuum bulb draws liquid into the pipette.

Another sampler which is similar to trombone sampler is bayonet sampler where in this case saran bottle is being used. After the bottle in place, the jet reduces the pressure in the chamber bottle alike during the recirculation period. When the jet is turn off, the chamber is vented by the return line and this forces liquid form chamber into bottle (9).

APPLICATION OF EJECTOR IN WASTE GAS TREATMENT PROCESSES

Simplicity in ejectors design and it has no moving parts, enable its application even in paper industries and in many other industries which have mentioned before. Post treatment or so called waste gases treatment processes also using an ejector to tackle their problems. Since the flow at exit of the nozzle is turbulence when motive fluid being used is air or reaction gases, a good platform has been created by ejector to mix the gases that it entrains efficiently.

Example of application is gas pollutants removal in single and two-stage ejector-venturi scrubber. At the same time, several methods are also available for the control of particulate matter from flue gases such as cyclones, settling chamber, fabric filter and electrostatic precipitator. Amongst the wet scrubber, the venturi scrubber is unique in that it is not only efficient for the collection of particulates but can also function as a gas absorber (10).

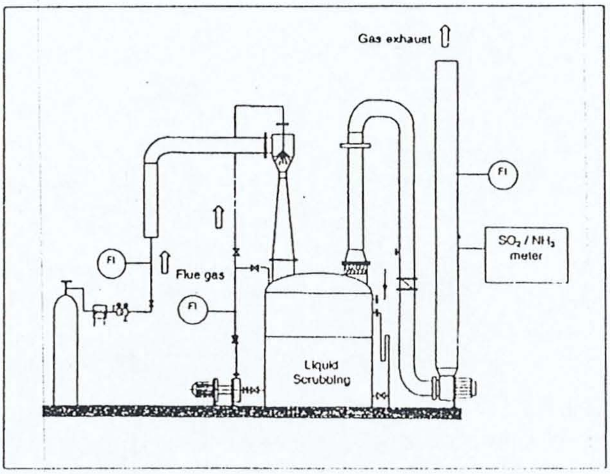

Figure 5: Ejector-venture scrubber pilot plant

Figure 5 is shows the ejector-venturi scrubber pilot plant. The design was based on a mechanical atomization principle, where a pressure-swirl atomizer was used. Jet effect is been created by water (aqueous solution) spray nozzle. The result is an induced air flow through scrubber. At this point, gas and liquid enter the throat, where extreme turbulence is encountered and continue through the diffuser section where partial separation of the gas and liquid occur. The aim of this design is to remove or reduce the pollutants level (SO_2 and NH_3) in stack gas [10].

Basically the principle of operation of ejector is same and by modifying the location of ejector in process flow, the desired objective is possible to achieve in the waste gas treatment processes.

CONCLUSIONS

This article is a brief explanation of ejector working principle and areas that it has been using extensively. The paper is written in very fundamental approach and the purpose is to give an exposure to new researcher and industries about potential of using this ejector in tackling environmental related problems. Theoretical studies are different for each case and basically looking for higher entrainment ratio in each design that has been made.

NOTATION

P = pressure (Pa g)

g = acceleration due to gravity (ms^{-2})

Z = elevation above datum (m)

v = velocity (ms^{-1})

ρ = density ($kg\ m^{-3}$)

R = universal gas constant

γ = specific heat ratio

$\dot{m}$ = mass flow rate

A = area

Subscripts

o,1 = inlet of nozzle

s = Suction port

c, 2 = outlet of diffuser

REFERENCES

1. Sun, Da-Wen and Eames, I.W (1995). Recent development in the design theories and applications of ejectors-a review. Journal of the Institute of Energy. 68 (475), 65-79.

2. Mote, R.G. "Air movement and vacuum devices". Process equipment series, Technomic Publishing Company, U.S.A., 3, 216-269.

3. Sun, Da-Wen, Eames, I.W and Aphornratana, S,(1996), "Evaluation of a novel combined ejector-absorption refrigeration cycle-I: computer aided simulation", Int. J. Refrigeration,19, 172-180.

4. Lear, G.M; Parker, G.M and Sherif, S.A (2002). "Analysis of two-phase ejectors with Fabri chocking" Proceeding of the Institution of Mechanical Engineers; London.

5. Karassik, I.J., Krutzsch, W.C. and Fraser,W.H. (1976) Pump Handbook, McGraw-Hill Book Company, 4, 1-23 6.

6. Shapiro, A.H. The dynamic and thermodynamic of compressible fluid flow, John Wiley and Sons, U.S.A, 1, 45.

7. Wang, D and Wypych, P.W. (1994) "Water-only performance of proportioning jet pump for hydraulic transportation of solids". Powder Technology. 85, 57-64.

8. Sun, Da-Wen and Eames, I.W (1995). "Recent development in the design theories and applications of ejectors-a review". Journal of the Institute of Energy. 68 (475), 65-79.