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Incinerator System for Spent Reverse Osmosis Membrane Management: Conceptual Design and Feasibility Study

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Abstract: Desalination of sea water using selectively permeable reverse osmosis membrane modules has emerged as a possible long term solution to the global problem of potable water shortage. These aromatic polyamide based modules have a useful working life of about 2-3 years and the spent membranes will have to be handled at the desalination plant site itself. An on-site incineration plant with advanced flue gas conditioning and immobilization provision has been proposed as the solution to this problem. The polymeric membrane modules will be completely converted to carbon dioxide, nitrogen and water vapour upon combustion, thereby significant reduction in solid waste volume will be attained. This work presents a simplified analysis to estimate the quantity of waste to be handled by the incinerator, material and energy balances for conceptual design of the incineration plant and its carbon dioxide capture system and addresses the associated techno-commercial feasibility aspects of such a facility. Energy recovery from the combustion chamber has also been considered in this study. The methodology presented here will be useful for quick sizing and feasibility study of an incineration plant for other kinds of solid wastes with known combustion characteristics as well.

Keywords: Desalination, Flue gas, Incinerator, Reverse osmosis, Spent membrane, Waste to energy.

I. Introduction

Safe potable water is a necessity for sustaining life but it is increasingly becoming a scarce resource all over the world. Ever increasing human population and growth of industries and associated environmental pollution issues have been major contributors to this scarcity, affecting urban and rural centers alike all over the world. Almost two-thirds of the earth's surface is covered with water but this water is not directly usable for drinking purpose because of the high content of dissolved salts. In such a situation, purification and desalination of sea water provides us with an option, possibly the only option in a long term framework, of obtaining potable water and ensuring water security. Globally, a large number of desalination plants have been set up along coastal areas or areas where salt water lakes and lagoons exist and they are partially meeting water supply requirements of people and communities residing in the vicinity of these desalination facilities [1]. Some of the larger desalination plants have production capacities varying from 10 to 30 million gallons per day, with several more such plants being constructed around the world. It is expected that the number and capacities of such facilities will only increase in the near future in order to cope with the growing demand for fresh water.

Currently there are two major categories of technology available for sea water desalination - thermal technologies (which use thermal energy or heat to evaporate sea water and produce water vapour which can be condensed to give fresh water) and membrane technologies (which use phenomena like reverse osmosis (RO) based on special cellulosic and polymeric membranes to produce fresh water) [2]. Both these technologies are mature and widely used at industrial scales. Coastal sites are also favourable locations for nuclear power plants and nuclear waste heat has been proposed extensively as a potential source of thermal energy for sea water desalination plants [3]. Thus integrated desalination facilities where both membrane-based and thermal techniques for producing fresh water from sea water can be a value-added feature of coastal power plants.

Owing to the fouling of desalination membrane modules and degradation in their separation performance due to exposure to high salinity, these modules have to be replaced after their useful life of 2-3 years. There are several manufacturers of such modules [4-6] and at a typical desalination plant, several hundred to several thousand such modules may be used together to meet the desired throughput. Thus annually a large amount of waste or discarded membrane modules may be generated at the site of the desalination plant. It is important to manage this waste at the site instead of further burdening existing solid waste management facilities or diverting it to landfills.

In this work, the waste disposal aspects of the spent reverse osmosis membranes are addressed at a conceptual level. This issue has not been addressed extensively by developers or users of the membrane systems but it is imperative to do so in the near term. One of the schemes proposed in this work is an on-site incineration system with energy recovery from the waste and carbon dioxide capture. Incineration is a well known and mature technology of dealing with solid wastes in almost all developed or developing countries of the world, which leads to significant volume reduction of solid waste and can even produce useful by-products and valuable energy [7, 8]. Thus it is one form of decentralized waste management system addressing a specific kind of waste. The typical membrane modules for sea water desalination are synthesized mainly using cellulose acetate or aromatic polyamide materials. These materials are combustible (albeit at high temperatures) and possess significant calorific value and at the same time, possibility of harmful products of combustion being generated from burning these modules is minimal, depending on combustion conditions chosen. Thus solid waste volume can be reduced greatly by incineration and the heat of combustion can be recovered gainfully in the incineration process itself for preheating combustion air using hot flue gases and further by production of electricity through a gas turbine or thermoelectric generator arrays. Moreover, using solid state CO_2 adsorbents such as hydrotalcites [9, 10], a passive and dry flue gas treatment scheme can be integrated with the incineration system, thereby further reducing the quantity and energy demands of secondary waste handling (which would occur if conventional alkaline solutions were to be used to scrub CO_2 from the flue gas stream of the incinerator). This in turn leads to significant reduction of the adverse environmental effects of spent membrane management by incineration technology. The technical feasibility and energy aspects of such a process scheme for a chosen incinerator plant throughput are examined in this work to arrive at a conceptual design.

II. Incineration System for Spent Membrane Management

A. Process Scheme

Fig. 1 shows the proposed schematic of the membrane incinerator system. Fresh air (about 20% excess over stoichiometric requirement drawn in from the atmosphere by a compressor) is passed through an economizer where it is preheated to about 150 deg C by heat exchange with the hot flue gases leaving the combustion chamber. It is then passed through an electrically heated air heater where its temperature is raised to about 600 deg C or more, depending on combustion temperature required by the membrane modules. The spent modules are shredded into pieces of about 1” to 1.5” using a mechanical shredder and the pieces are led into a conical feed hopper. The size of the shredded pieces should be small enough to ensure efficient combustion but not so small that they are entrained out of the system by the flowing combustion gases. From the hopper the desired weight of plastics is fed into the combustion chamber. Solid is fed batch wise while air flow remains continuous through the combustion chamber. Heated air and polymeric waste interact chemically and burning takes place, releasing heat of combustion and producing flue gases. These hot gases are first cooled by heat exchange with fresh air in the economizer, then passed through a bag house or HEPA filter to arrest particulate matter followed by passing through an adsorbent bed where most of the CO_2 and sulphur oxides if any get converted are trapped by chemical reaction with a hydrotalcites based material. The cleaned flue gases are then discharged through the stack of appropriate height. The solid residue from the incinerator, which is mainly derived from the inorganic constituents of the membrane modules, as well as the dust accumulated in the HEPA filters are collected, quenched in a water batch to form a solid mass which is then disposed of or used as raw material for construction. The CO_2 adsorber bed is not regenerated but its contents are disposed of to be used in producing cement or other construction materials, since it will be in carbonate and sulphite/sulphate form. Thus CO_2 emission from the incineration system is expected to be minimal. Additionally by avoiding a liquid based acid gas scrubbing system (as is conventionally used), secondary waste stream generation is minimized and capital and operating expenditure of the plant are also expected to be significantly reduced.

B. Plant Design Basis, Material and Energy Balances

Each component of the plant will have to sized on the basis of the batch of solids that will have to be combusted at a time, as well as on the total combustion cycle time proposed. The plant follows a semi-batch mode of operation, as described in the previous section. A simple spreadsheet based calculation module has been developed for preliminary calculations of material and energy flows in the incinerator plant, for user-defined batch size, combustion time and material type and associated thermal properties. An image is shown in Table I, where calculations for waste polypropylene material (simulated waste) are shown as an example. User inputs required for these calculations are batch size, fraction of carbon and hydrogen (the two primary combustible elements in the waste material) in the membrane module, per cent excess air for incineration, combustion temperature, specific heat of waste material, its moisture content and its enthalpy of combustion.

The incineration plant throughput will be decided based on the number of spent desalination membrane modules generated each year on site. This depends on the desalination capacity of the plant and the capacity of each individual membrane module. Some typical industrial RO membrane modules and their capacities are presented in Table II, based on membrane module datasheets available in literature [4-6]. For assumed sea water RO plant capacity of 50 million liters of fresh water per day (for a medium scale desalination plant), the approximate number of modules required has been estimated. Assuming 50% of these modules have to be replaced each year owing to performance degradation, the amount of spent membrane modules to be managed each year is calculated. This forms the basis of estimating the incineration plant capacity. It is observed that using typical commercially available industrial membrane modules (spiral wound, thin film composite type) of maximum capacity (8” diameter and 40” length) for sea water reverse osmosis will generate between 8000 and 15000 kg of polymeric waste annually at the site of the 50 million liter per day desalination plant. Hence an average value of 12000 kg per annum of plastic waste is taken as the feed flow rate to the incineration system. For a waste batch size of 20 kg and taking 2 hours as the total time for complete incineration, 10 kg/hr of waste has to be incinerated. Thus a total of 1200 hours of operation of the plant per year will be required and for continuous, round the clock operation, this translates into 50 days of plant operation per year. Continuous operation is desired in order to minimize repeated thermal cycling of the incinerator and allied systems. This therefore fixes the design basis of the waste incineration plant when operated annually on a campaign basis.

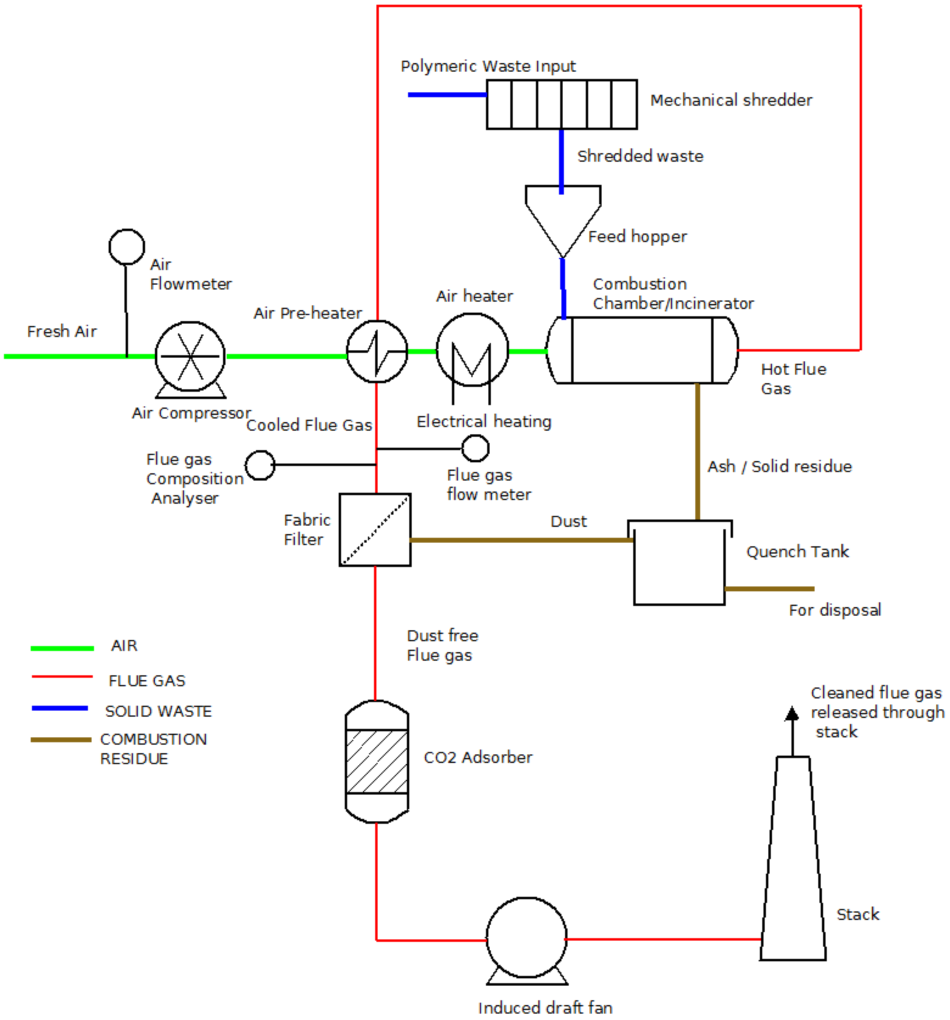


Fig. 1: Flow Sheet for Spent Reverse Osmosis Membrane Incineration System

A simplified representation of the incinerator plant for carrying out pseudo steady-state material and energy balances is shown in Fig. 2. The air pre-heater, air heater and combustion chamber are the only process units considered for this purpose and in actual operation, a semi-batch feeding method will be used for membrane module incineration. Air requirement and flue gas volume rate are calculated from stoichiometry, assuming complete combustion and no solid ash formation during burning. Heating requirement and heat release during combustion are estimated from thermochemical properties of typical aromatic polyamide materials, using spreadsheet calculator mentioned above. It has to be ensured that the air temperature is about 700 deg C before being fed in to the incinerator (since the polymer will ignite at about 600 deg C and mixing of heated air with cold waste feed will cause a sharp drop in temperature at the incinerator inlet) and this is used to specify the power output required from the air heater. Temperatures at various points are estimated by simultaneously solving energy balance equations 10-12. Temperature of feed air before and after preheating is taken as a design parameter and the remaining three temperatures are calculated.

$$M = 2.5 \text{ kg/hr} \quad (1)$$

$$M_o \sim 0 \text{ kg/hr} \quad (2)$$

$$Q = 72\frac{Nm^3}{hr}\left(\textit{from stoichiometry}\right) \quad (3)$$

$$Q_o = 76\frac{Nm^3}{hr}\left(\textit{from stoichiometry}\right) \tag{4}$$

$$T_1 = 30 \text{ deg } C \text{ (known inlet condition)} \tag{5}$$

$$T_5 = 130 \text{ deg } C \text{ (required flue gas exit condition)} \tag{6}$$

$$T_{\text{ref}} = 0 \text{ deg } C \text{ (reference temperature for enthalpy calculation)} \tag{7}$$

$$W = 14.5 \text{ kW (heat supply to combustion air via electrical heating)} \tag{8}$$

$$q = 42 \text{ kW (mean heat release rate inside incinerator during combustion)} \tag{9}$$

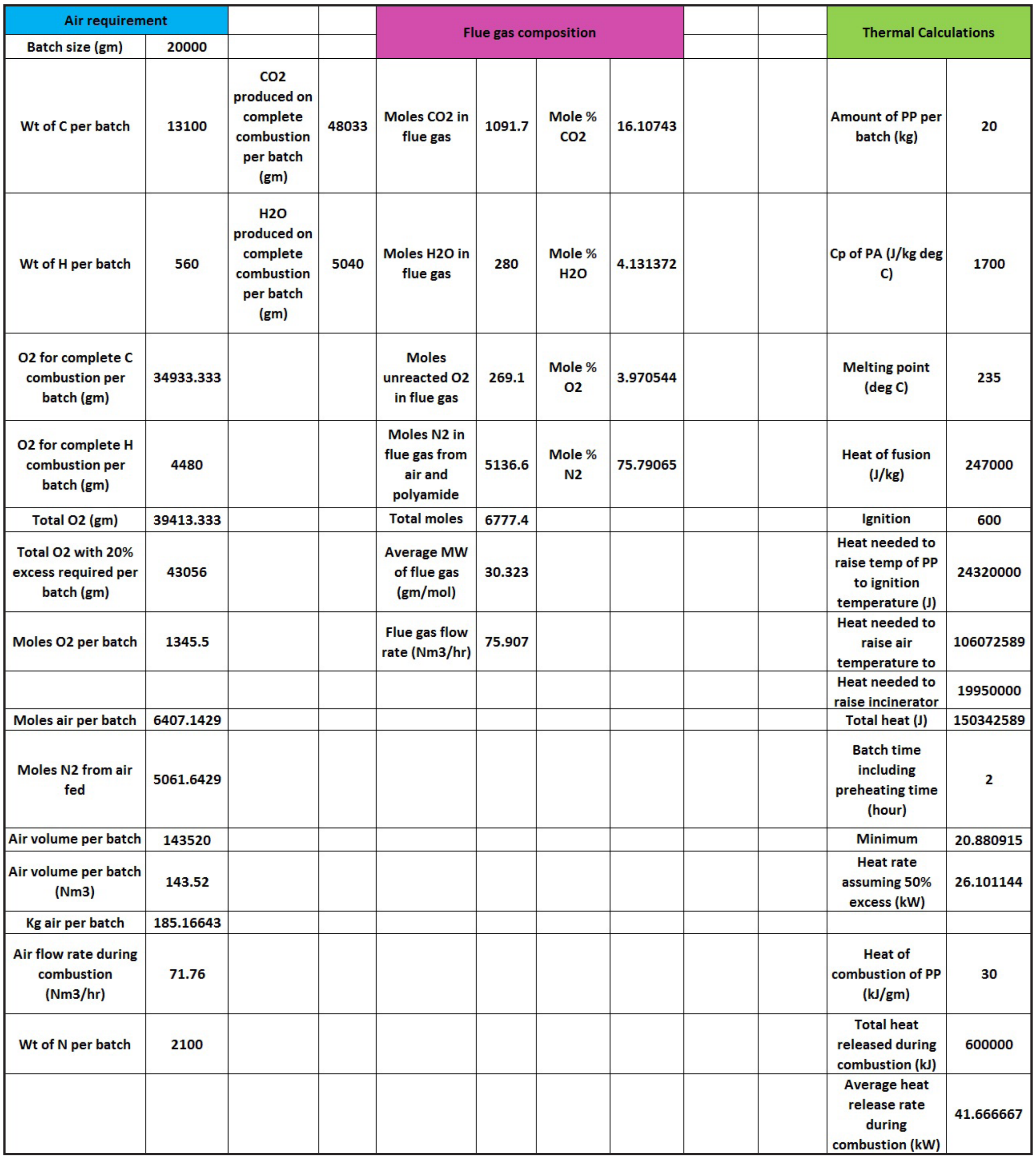
$$Q * C_{pa} * (T_2 - T_1) = Q_o * C_{pf} * (T_4 - T_5) \tag{10}$$

$$Q * C_{pa} * (T_2 - T_{\text{ref}}) + W = Q * C_{pa} * (T_3 - T_{\text{ref}}) \tag{11}$$

$$QC_{pa}(T_3 - T_{\text{ref}}) + MC_{ps}(T_1 - T_{\text{ref}}) + q - 0.25W - M\Delta H_f - MC_{ps}(T_3 - T_{\text{ref}}) = Q_o C_{pf}(T_4 - T_{\text{ref}}) \tag{12}$$

Reference material type for process calculations of the incinerator has been taken as aromatic polyamide formed from m-phenylene diamine and trimesoyl chloride [15] and its thermochemical properties have been used in all subsequent calculations, though actual membrane compositions may differ from manufacturer to manufacturer. Results are shown in Table III.

TABLE I: SPREADSHEET BASED CALCULATION TOOL DEVELOPED FOR MATERIAL AND ENERGY BALANCES IN POLYMERIC WASTE INCINERATION



Air requirement				Flue gas composition						Thermal Calculations	
Batch size (gm)	20000										
Wt of C per batch	13100	CO2 produced on complete combustion per batch (gm)	48033	Moles CO2 in flue gas	1091.7	Mole % CO2	16.10743			Amount of PP per batch (kg)	20
Wt of H per batch	560	H2O produced on complete combustion per batch (gm)	5040	Moles H2O in flue gas	280	Mole % H2O	4.131372			Cp of PA (J/kg deg C)	1700
O2 for complete C combustion per batch (gm)	34933.333			Moles unreacted O2 in flue gas	269.1	Mole % O2	3.970544			Melting point (deg C)	235
O2 for complete H combustion per batch (gm)	4480			Moles N2 in flue gas from air and polyamide	5136.6	Mole % N2	75.79065			Heat of fusion (J/kg)	247000
Total O2 (gm)	39413.333			Total moles	6777.4					Ignition	600
Total O2 with 20% excess required per batch (gm)	43056			Average MW of flue gas (gm/mol)	30.323					Heat needed to raise temp of PP to ignition temperature (J)	24320000
Moles O2 per batch	1345.5			Flue gas flow rate (Nm3/hr)	75.907					Heat needed to raise air temperature to	106072589
										Heat needed to raise incinerator	19950000
Moles air per batch	6407.1429									Total heat (J)	150342589
Moles N2 from air fed	5061.6429									Batch time including preheating time (hour)	2
Air volume per batch	143520									Minimum	20.880915
Air volume per batch (Nm3)	143.52									Heat rate assuming 50% excess (kW)	26.101144
Kg air per batch	185.16643										
Air flow rate during combustion (Nm3/hr)	71.76									Heat of combustion of PP (kJ/gm)	30
Wt of N per batch	2100									Total heat released during combustion (kJ)	600000
										Average heat release rate during combustion (kW)	41.666667

Table II: Typical Commercially Available Industrial RO Membrane Modules

Manufacturer	*Type*	*Materials*	*Desalinated water production capacity of each module*	*Approximate drained weight of each module*	*Minimum number of modules required for 50000 m^3/day desalination plant*	*Approximate weight of spent membrane modules generated per year*
Hi-tech Membranes, Thailand	Polyamide thin film composite membrane (Model: BW30-400)	Polyamide, vinyl ester	40 m^3/day	11.8 kg	1250	9063 kg
Dow Filmtec, United States of America	Polyamide thin film composite membrane (Model: FILMTEC SW30HR-380)	Polyamide, vinyl ester	23 m^3/day	11 kg	2174	11957 kg
Daicen Membrane Systems Limited, Japan	Spiral wound, synthetic composite membrane (Model: DRA9810)	Polyamide, vinyl ester	35.6 m^3/day	11.5 kg	1405	8080 kg
Koch Membrane Systems, United States of America	Spiral wound, thin film composite membrane (Model: 8040-SW-440-28)	Polyamide, vinyl ester	30 m^3/day	17 kg	1667	14170 kg

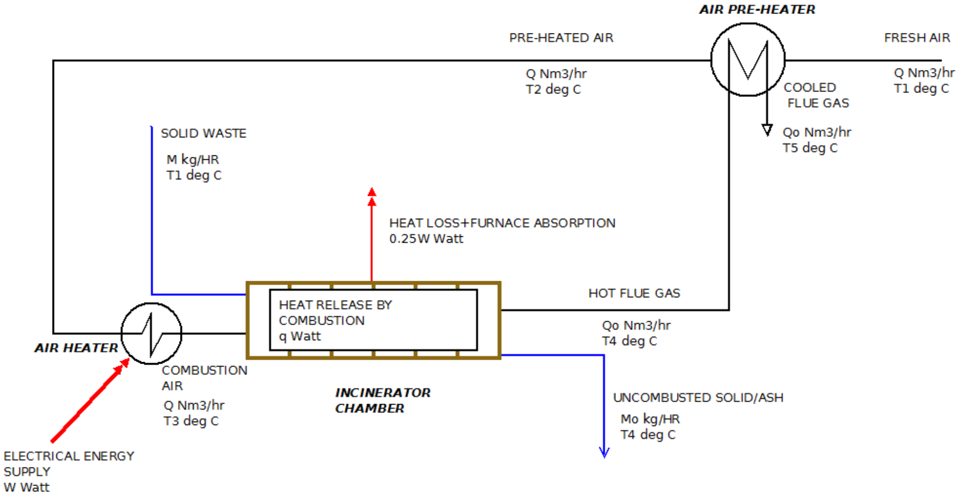


Fig. 2: Incinerator Plant Schematic for Pseudo-Steady State Material and Energy Balances

Table III: Material and Energy Balances for Incineration Plant

Parameter	*Value/Range*	*Remarks*
Weight of waste charged per batch	20 kg	Batch sizing criteria discussed above
Thermochemical properties of waste	Density : 1.14 gm/cc, Specific heat : 1700 J/kg K, Melting point: 235 deg C, Heat of fusion, Combustion temperature: 532 deg C, Heat of combustion: 30 kJ/gm	Values obtained from literature [11, 12]
Combustion batch time	2 hours (including preheating time)	Decided on the basis of peak power requirement for incineration
Solid feeding rate	10 kg/hr	Annual capacity when operated continuously with 100% availability = 88 tonnes per annum

Parameter	*Value/Range*	*Remarks*
Elemental composition of waste	Aromatic polyamide with 65.5% C, 2.8% H, 10.5% N, 21.2% O	Aromatic polyamide synthesized from m-phenylene diamine and trimesoyl chloride considered as the polyamide material for the membrane modules
Air quantity required for complete combustion of waste batch, assuming 20% excess air	186 kg	C and H have been taken as the elements participating in combustion, formation of nitrogen oxides not explicitly considered
Air flow rate required during combustion	72 Nm^3/hr, for 2 hours batch time	Total air quantity required has been assumed to be fed over 2 hours
Flue gas flow rate	76 Nm^3/hr, for 2 hours batch time	Total amount of flue gas from material balance calculations released over 2 hours has been assumed
Flue gas composition (Mole %)	CO_2 : 16.1%, H_2O : 4.1%, O_2 : 3.97%, N_2 : 75.8%	Combustion equation considered for flue gas composition estimation is as follows: $C_cH_hO_mN_n + (c+(h-2m)/4)O_2 = cCO_2+(h/2)H_2O+(n/2)N_2$
Furnace/flue gas exit temperature	1430 deg C	Obtained by material and energy balance calculations, assuming furnace contents and flue gas to be well mixed and in thermal equilibrium at the incinerator discharge end.
Heat absorbed by furnace	15% of thermal input	Heuristics based calculation
Heat losses	10% of thermal input	Heuristics based calculation
Energy supply rate required for complete incineration	14.5 kW	Energy required for each step like heating solid waste up to melting point, heat of fusion, heating to combustion temperature has been accounted for, along with losses.
Average energy release rate from waste during combustion	41 kW	Heat release before incineration is initiated is taken as nil and peak heat release rate is calculated from total and instantaneous combustion of the waste. The average heat release rate is the arithmetic mean of these two rates. In reality this rate will be non-uniform and will depend on prevalent combustion kinetics.

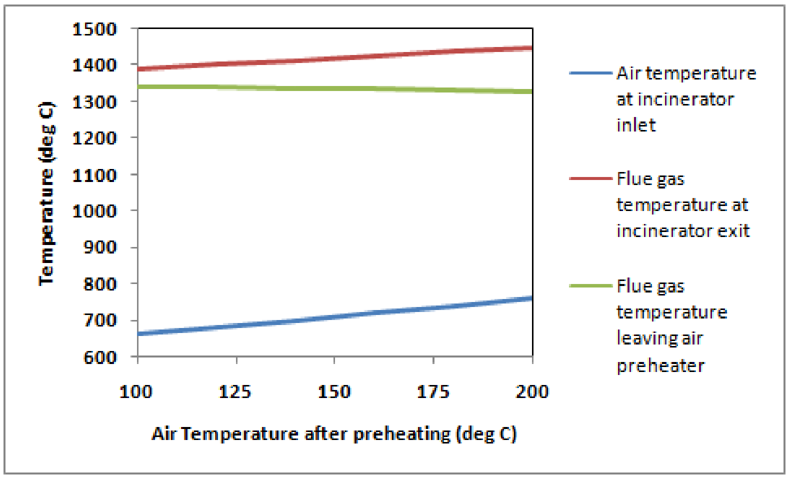


Fig. 3: Effect of Combustion Air Pre-Heating on Flue Gas Temperature for Heat Input of 14.5 kW

Design basis calculations for sizing every major equipment or system in the process schematic, based on the design basis batch size previously determined have been performed and the results are shown in Table IV. These are tentative sizes of the process equipment in order to estimate project costs.

TABLE IV: DESIGN DATA FOR MAJOR COMPONENTS OF INCINERATOR PLANT

Equipment	*Design Basis*	*Specifications*
Incinerator Chamber	Must accommodate the solid waste charge of 20 kg per batch, gas residence time of at least 2 seconds to ensure complete combustion and destruction of dioxins and furans	Chamber volume = 50 L based on gas residence time, cubical chamber with front opening door, length = depth = height = 0.37 m, air face velocity = 0.58 m/s at 700 deg C inlet temperature
Heating Arrangement for Incinerator	Indirect fired incinerator considered, heating system should be able to supply 15-20 kW of thermal energy to air heater (electrically heated)	High temperature open coil duct air heater with radiation and convection based air heating capability, duct area = 0.01m^2 corresponding to gas velocity of 10 m/s for combustion air throughput of 80 Nm^3/hr, 20 kW output power, Inconel sheath based heating element, 20 W/in^2 heat flux (total heat transfer area = 0.7 m^2)
CO_2 Adsorber Bed	Dry adsorption system required, adsorbent chosen should react with CO_2, must adsorb CO_2 generated over 60 days of incinerator operation	CO_2 adsorption modules each having 70 kg of hydrotalcites will be required for use, about 1850 modules will be required for 50 day campaign. Thus one module will have to be replaced by a fresh one every 1.5 hours.
Air Compressor	Should supply fresh air at the design flow rate decided by excess air requirements from material and energy balances	Required air flow rate = 80 Nm^3 hr^{-1}, discharge pressure to be developed = 3 bar (a), wetted parts must have material of construction capable of withstanding 1500 deg C temperature
Induced Draft Fan	Should draw out flue gases through the entire flue gas handling circuit	Required air flow rate = 100 Nm^3 hr^{-1}, discharge pressure to be developed = 3 bar (a), wetted parts must have material of construction capable of withstanding 1500 deg C temperature
Air Pre-Heater	Should pre-heat air with hot flue gases to a temperature of about 140 deg C	Welded plate, 1-1 pass, compact heat exchanger, 4 kW heat duty (gas-gas), material of construction should be capable of withstanding 1500 deg C temperature
Feed Hopper	Must be capable of feeding 10 kg/hr of shredded polymeric wastes into the incinerator	Feed hopper is to be in the shape of a truncated cone, manual feeding of shredded polymer waste from outlet of the shredder unit via buckets/bins. This system can be automated at a later stage for larger capacity plants.
Fabric Filter	Must remove particulate matter having size below 1 micron with efficiency greater than 99%, face velocity of air through filter should be about 0.5 m/s at the cooled flue gas exit conditions [13]	Surface area of the high temperature resistant ceramic filter fabric = 0.3 m^2, should be placed inside a common housing with a conical bottom. Provision for air jet injection to clean the fabric filters and gather the collected dust is also required.

Since the gas flow rate is about 80 Nm^3 hr^{-1} for air side and flue gas side, the economical pipe diameter calculated is 50 NB. All air supply and flue gas pipes should be fabricated out of Inconel which is suitable for high temperature operation. Microtherm insulation of 2” thickness will be required on all high temperature pipelines.

It is seen from Fig. 3, the temperature of the flue gas remains at about 1350 deg C even after using it for pre-heating incoming air. The thermal energy content of this gas temperature should be recovered via production of steam through a waste heat boiler and generation of electricity through a typical power producing Rankine cycle and/or through thermoelectric generation. The generated electricity can be used for the electrically heated air heater in the incineration system for significantly improving the energy efficiency of the process.

C. Energy Aspects of Membrane Incineration Plant

The incineration process requires energy to be initiated and subsequently produces thermal energy according to the heat of combustion of the material being burnt. The heat released during combustion can be recovered by pre-heating the incoming air, thereby making the process more energy efficient. The concept of waste to energy (as a specific example of the waste-to-wealth concept) is emphasized in the design and operation of the incineration plant, particularly when it is proposed to be an auxiliary system of an already energy intensive process operation like sea water desalination. Yet another way of making incineration an energy-wise more viable option is to use renewable energy systems like solar photo-voltaic systems or wind turbines to generate electrical power for electrically heating the combustion chamber or concentrating solar thermal systems to generate high temperature fluid streams suitable for air-heating. For the 20 kg polymer batch size and 2 hours batch time that has been used as the design basis in this work, total input power requirement for the entire incineration plant is estimated to be about 15 kW, which can suitably be met by a single or at most a pair of micro wind turbines located alongside the incineration plant [14]. More precise details can be fixed once a site of the desalination and incineration plants is fixed and its wind energy harvesting potential is thoroughly examined. This can make the incineration plant power grid independent as well. Wind turbines will be particularly efficient for such plants located in coastal regions since wind velocities are higher in these locations (thereby offering the possibility of higher power generation than in inland locations) and they will require much less land area than solar photovoltaic or solar thermal plants of equivalent capacity. In future, even off-shore wind turbines can be deployed for similarly located larger incineration plants dealing with similar wastes.

A large amount of thermal energy is carried by the exhaust flue gas. Even after recovering a part of it (4 kW) by preheating the fresh combustion air, it has a temperature of about 1350 deg C. Assuming that it can be sent through a gas turbine to produce electricity via a gas power cycle and cooled finally to 30 deg C, the maximum thermal to electrical energy conversion efficiency that it can have is given by Carnot's law and it is equal to 81.3%. A real gas power cycle may have about 30 to 40% of this efficiency. Thus a maximum of 32.5% of the exhaust flue gas's thermal energy can be converted to electricity. For a flow rate of 76 $Nm^3\ hr^{-1}$, electrical energy output from this cycle can be about 2 kW. Thus total 6 kW energy savings may be achieved (i.e. 40% of the 15 kW electrical energy input needed for preheating of air). Using thermoelectric generators operating between 1350 deg C and 30 deg C ambient heat sink (which are about 10% efficient in this temperature range), the maximum energy recovery possible is 0.62 kW. Thus electricity production from hot flue gas does not seem techno-commercially very feasible for this particular scale of waste incineration plant, though the feasibility must be examined for larger scale plants (1000 tons per annum and above of waste handling capacity).

D. Flue Gas Handling

Incineration of polymeric membrane produces $CO_{2,}$ moisture and other volatile oxides, thus the incineration plant has to take care of emission of these species as part of its flue gas handling system. Other than that, high efficiency particulate active filters are required to remove dust particles from the flue gas stream before chemical treatment. Globally efforts are being made to bring down green house gas CO_2 emissions by practice of carbon dioxide sequestration. This idea has been applied in the conceptual design of this incineration plant because it too is a stationery source of concentrated CO_2 emissions, much like existing goal or natural gas fired thermal power plants. Considering flue gas flow rate of about 80 $Nm^3\ hr^{-1}$ with a CO_2 content of 17%, the total amount of CO_2 to be adsorbed over 60 days of operation is 19584 Nm^3 or 38780 kg. For a hydrotalcites type material capable of adsorbing up to 30% by weight of CO_2, this will require about 129270 kg hydrotalcites per annual incineration campaign [17]. Considering 70 kg modules of the solid adsorbent, about 1850 modules will be required for each campaign with 37 modules required per day.

III. MEMBRANE INCINERATION COSTS

The operating cost is primarily based on the electrical energy needed to pre-heat air, run the air compressor and the induced draft fan. At ₹10/kWhr of electricity obtained from the grid, electricity cost per annual incineration campaign is at about ₹300000. The cost of waste transportation will be minimal since the plant will be located very close to the site of waste generation and is hence neglected. The fixed capital investment is required for all the units in the waste incineration scheme. The typical cost of incineration plant depending on the scale of waste handling is available in literature for large to medium scale plants [16]. Using the same cost correlation for a small scale plant, for 88 tons of waste per annum capacity, the cost is around $ 4000 per ton per annum. Thus the fixed cost of the plant will be about ₹2.5 crore, assuming 1 US $ = ₹70. Assuming a plant life of 20 years and depreciation of 5% on the fixed capital investment and 20% of operating capital investment as annual O&M costs, the total annual capital investment for the waste incineration plant is $₹1.7*10^6$ per campaign. This translates into a minimum expenditure of ₹135/kg of polymer waste processed by incineration per campaign. The cost will be different if renewable energy sources are considered to be used for meeting the plant's energy requirements, as discussed earlier.

IV. SUMMARY AND CONCLUSIONS

Management of spent reverse osmosis based desalination membranes modules is emerging as a challenge at every desalination plant. These modules are high calorific value polymer based structures and hence incineration is one way of dealing with them. These plants can be co-located at the desalination facility itself. For a typical 50 million litre per day of RO based desalination plant, polymer waste generated is about 12000 kg/year. This requires an incineration system handling 10 kg/hr of waste and consuming about 15-20 kW of electrical energy for creating the incineration temperature of 600-700 deg C. For such a plant, at least about 4 kW of energy can be recovered from the hot flue gases in pre-heating the combustion air and emission reduction of 38780 kg CO_2 can be achieved by trapping it over a highly adsorbent solid matrix. The levelised waste disposal cost by this technology is about ₹135/kg, though it is expected to be higher when also including advanced CO_2 capture technologies in the facility (calcium oxide captures up to 44% by weight of CO_2 and costs about ₹30/kg, which translates into additional expense of ₹105 per kg of waste incinerated). Alternative uses for these high quality polymer components should be considered first before destructive waste management is adopted. These can also be burn in an existing thermal power plant alongside coal or other solid fuel without having to develop a separate waste incineration plant, though this will require that the spent polymer modules be specially transported to the site of the power plant. Like most chemical plants, waste incineration plants also exhibit economies of scale and the overall scheme will be more profitable for a larger waste management plant at a larger desalination plant site.

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NOMENCLATURE

c	Stoichiometric coefficient of carbon atoms in the waste polymer, dimensionless
C_{pa}	Specific heat capacity of the combustion air, kJ/kg K
C_{pf}	Specific heat capacity of the flue gas, kJ/kg K
C_{ps}	Specific heat capacity of the solid waste, kJ/kg K
h	Stoichiometric coefficient of hydrogen atoms in waste polymer, dimensionless
m	Stoichiometric coefficient of oxygen atoms in waste polymer, dimensionless
M	Pseudo-steady state feeding rate of the solid waste into incinerator chamber, kg/hr
M_o	Pseudo-steady state exit rate of the uncombusted solid waste/slag out of the incinerator chamber, kg/hr
n	Stoichiometric coefficient of nitrogen atoms in waste polymer, dimensionless
q	Average heat release rate inside incinerator chamber during combustion reactions, W
Q	Combustion air flow rate, Nm^3/hr
Q_o	Flue gas flow rate, Nm^3/hr
T_1	Temperature of fresh combustion air, ^oC
T_2	Temperature of combustion air after pre-heating, ^oC
T_3	Temperature of combustion air after heating before entry into combustion chamber, ^oC
T_4	Temperature of flue gas leaving incinerator, ^oC
T_5	Temperature of flue gas after heat exchange with fresh incoming combustion air, ^oC
T_{ref}	Reference temperature for enthalpy calculations, ^oC
W	Energy input rate from electrical heater to combustion air, W
ΔH	Heat of combustion of the polymeric waste, kJ/kg K

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