IPRO It takes a team INTERPROFESSIONAL PROJECTS PROGRAM

IPRO 497 – 302

Analysis of Water Recovery from Power Plants for Recycling

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Sponsored by:

Sargent & Lundy LLC

1. Abstract

Potential power plant sites can become more difficult to determine if water is not available in great quantity. This is true in western states where it may be scarce and competed for by other industries as well as households. The aim of this project is to find an economical, as well as environmentally friendly way to recover water from the flue gas, which is produced when powder-river-basin (PRB) coal is burned in a 750 MW power plant.

To address this problem, we will organize into Groups, research direct contact and indirect contact methods, and ultimately provide capital costs, operational costs, and specification estimates for each design.

2.0 Background

A. Sargent & Lundy L.L.C. is a leader in the global community of industrial power. They have served the global community as consultants and engineers of power delivery from coal, oil, gas, nuclear, and other sources of energy and design of pollution controls. Currently, a majority of their expertise and contracts are devoted to coal power generation that gives rise to this given project.

B. Sargent & Lundy L.L.C. is currently retro fitting a 750 MW coal fired power plant that utilizes PRB coal. When coal at a power plant is burned, the heat is used to generate power and a side product of this burning is the flue gas, which contains a lot of pollutants. At this time a majority of power plants use nearby bodies of water such as lakes, rivers, and oceans to remove heat from the power plant. Water is also used in Flue Gas Desulfurization (FGD) systems that remove sulfur components and other pollutants from the flue gas before it's released into the air. Building a new FGD system for this power plant would be difficult as water is scarce in the area and expensive to buy, so Sargent and Lundy L.L.C. wish to recover water from the flue gas. The goal of this project is to recover as much water as possible the flue gas and determine cost-effectiveness as well as operation viability. The water, once removed, is then to be recycled within the power plant to be used in processes such as the FGD system, flue gas cooling, or transported for cleaning.

C. Current methods of removing liquid water from a gas involve the exchange of heat indirectly (conduction of heat through a cooled solid) or directly (convection of heat directly in contact with a gas/fluid), forcing gas through membranes, or using desiccants to absorb the water, which can be removed later. Through direct and indirect contact cooling, the flue gas is to be cooled past the dew point of water (temperature that steam begins to condense to liquid) to in order to recover it. Various heat exchanging systems as well as other alternatives will be recommended and evaluated for cost-effectiveness and viability at the conclusion of the semester. In addition, the best location for water removal (before or after the installed FGD system) will be evaluated and recommended. Evaluations include an analysis of the quantity of moisture in the flue gas and cost estimates (capital and operational). This includes additional information such as added pressure drops of new equipment and the quality of water produced in each design.

D. Some potential ethical issues had to be kept in mind during the semester while working on the project. We had to keep in mind the Federal, State, and Local regulations so as not to infringe on copyright laws or environmental laws. Lack of time was also an issue because all of us had other responsibilities such as school and work and we could have neglected our work on the project, which could have ended in insufficient progress at the end of the semester or we could have been enticed to misrepresent our reported work hours and, wrongfully claim credit for work done. The impact on the communities in the immediate surrounding area always had to be taken into account especially when working on the flue gas or water reservoir. Respect for our contacts, sources, and especially team members needed to be observed throughout the semester; without cooperation and understanding within the team, this project would not have been possible.

3. Objectives

Our sponsor, Sargent & Lundy, has provided us with power plant specifications to work with, and informed us of exactly what they would like to see. To address the problem, we will organize into groups that will focus on certain aspects of the project. Currently we have two groups working on direct contact cooling, and indirect contact cooling. The members of these groups will be working on research, deliverables, etc.

Direct Contact Group:

- Research new and existing direct contact cooling methods after FGD (flue gas desulfurization). Direct Contact example – spray water into flue gas to cool water vapor down.

Indirect Contact Group:

- Research new and existing indirect contact cooling methods before and after FGD. Indirect Contact examples – fans cooling down the piping through with the flue gas travels, or condensing heat exchanger.

Additional things to research:

- Range of viable advanced technologies.
- Economics and scale of each design plan, which includes startup and capital costs.
- Cost per 1000 gallons of water produced.
- Alternative methods such as membranes, desiccant processes, and others.
- Find how much H_2O is required for FGD.

4. Methodology

A. *Work breakdown structure*

Analysis/Modeling

a.) Direct contact cooling methods after FGD 108 hours

b.) Indirect contact cooling methods after FGD 98.5 hours

c.) Indirect contact cooling methods before FGD	8 hours
d.) Other technologies (membranes, dessicants, etc.)	12 hours
Determine cost of H_2O	26 hours
Capital Cost estimates	32 hours
Operating Cost estimates	28 hours
IPRO Preparation (documentation, poster, etc.)	43 hours
IPRO Day	52 hours
TOTAL HOURS	**407.5 hours**

B. *Dates and deadlines*

September 17/18	Sargent & Lundy Project Plan due
September 19	Project Plan due on iGroups
September 23	Indirect group heat analysis of flue gas and water
September 25	Direct Group determine amount of heat in Flue Gas
September 30	Heat exchanger designs and intermediate stage of post FGD analysis
	Direct Group Estimate Cost of Cooling for Flue Gas based off Spray Tower design
October 2	Indirect cooling prior FGD analysis and design of water removal
	Direct group Determine price of water produced
October 7	Midterm Review
October 14	Begin making cost estimations and design comparisons
December 1	Exhibit Poster and Brochures due on iGroups
December 4	Presentation Slides due on iGroups
December 9	Final Report/Team analyses due on iGroups
December 9	Deliverables on CD due

C. For this project, we were presented with adequate power plant data for a 750MW coal-fired power plant, including its installed systems and operational parameters by our sponsors Sargent and Lundy. The following is a summary of the data available to us at the start of the project.

These data were used as a starting point for our calculations. We first used these data to calculate the flue gas composition after combustion in the boiler. Here, we assumed the air leakage into the boiler to be simply an added excess air for combustion, giving us a 33.6% excess air. After obtaining the flue gas composition, assuming an FGD with an efficiency of 99% and that the electrostatic precipitator removes all ash content, we used HYSYS to determine the amount of heat needed to be removed from the flue gas to drop its temperature from 350 °F to 100 °F. This value will be used later by both direct and indirect contact teams since both teams would use similar design parameters. Besides that, both teams decided to use water as the coolant. Since the amount of heat needed to be removed was the same, the amount of water needed to remove this amount of heat was the same, about 5590 kg/s.

Input Data		
Coal Analysis		**Design Parameters**
Components	**Weight (%)**	-Plant Heat Input = 7538000000 Btu/hr
Carbon	51.46	-Excess Air For Combustion = 20 %
Hydrogen	3.41	-Air Leakage Into Boiler = 13.6 %
Nitrogen	0.73	-Water In Air = 0.013 lb/lb of dry air
Sulfur	1	-Design Ambient Temperature = 80^{0}F
Oxygen	10.5	-Flue Gas Temperature Before FGD = 350^{0}F
Chlorine	0.01	-Atmospheric Temperature = 13.05 psia
Moisture	27.1	-Pressure At ID Fan Outlet = 9" w.c
Ash	5.8	-Pressure At FGD Outlet = 1" w.c
		- Higher Heating Value = 8826 Btu/lb

Direct Contact

To begin our analysis of a direct contact-condensing method, we first had to choose a direct contact method to outline the design of our system. Due to the nature of the power plant system presented to us by our sponsors, we were limited to systems that have minimal pressure drop, and thus we came up with the simple spray tower system that allows for negligible pressure drop and a simple construction and maintenance process. The lack of internals within the system translates into a low risk of fouling and corrosion within the system.

To determine the size of the spray tower, we first performed an analysis of a single water droplet within the tower, upon which its results would be integrated over the entire tower. The required terminal velocity of the droplet and its residence time based on the minimum time required for it to change from its initial to final temperature was determined. For this, mass, energy and momentum balances were developed for the droplet. A flue gas velocity within the spray tower was also determined. These calculations were effectively performed on a trial-and-error optimization basis, as important variables such as tower diameter, final water temperature and water droplet diameter were assumed. With this information, it was possible to determine the minimum height for the spray tower (without taking the collection system into account). Next, we had to add space within our spray tower to collect the water to facilitate the pumping of this water back up the height of the tower and through the spray nozzles. With the information on the density of carbon steel[6] and the price of installing a simple spray tower based on a mass-of-carbon-steel basis[3], we were able to determine the capital costs of constructing the spray tower. We also made an estimate of the capital costs of purchasing the pumps, although this was based on a weighted average of the different costs we were given from different manufacturers. All other costs with regards to initial capital were deemed to be negligible.

Next, we had to determine our annual operational costs, which were expected to be relatively high for spray systems[5].The cost of operating the pumps were deemed to be the most significant, and all other operational costs were expected to be negligible in comparison to this. Since we were provided with a cost of electricity on a kilowatt-hour basis, we determined the total power requirements of the pump, and came up with an overall estimate of the operational costs per year. The capital recovery factor provided to us by our sponsors was then used to annualize the costs to construct and operate a spray tower. Once this was done, a simple conversion was made to determine the cost of recovering 1000 gallons of water based on our water-recovery rate in the tower.

Indirect Contact Cooling

At the beginning of this project, our sponsor Sargent & Lundy specified two water recovery methods to look into, the indirect contact cooling and direct cooling method. For an indirect contact type heat exchanger, the hot flue gas and coolant streams remain separate, and the heat transfer takes place continuously through a heat transfer surface. There are some common indirect contact heat exchanger such as direct transfer type, storage type, and fluidized bed exchangers. After carrying out some research on those types of heat exchanger, it is determined that the most common and suitable type of heat exchanger would be the direct transfer heat exchanger. Among the different direct transfer type heat exchangers are tubular, plate-type, and extended surface exchangers.

In general, plate-type heat exchangers usually provide more surface area compared to other equivalent heat exchanger types, however, the operation of plate-type heat exchangers is unsatisfactory in high pressure and temperature conditions, or in cases where aggressive reacting fluids are present and thus this type of heat exchanger is generally used in small scale applications. There are two types of extended surface exchangers commonly found in the industry; the tube-fin air-cooled condenser and plate-fin cryogenic condenser. The tube-fin air-cooled condenser was identified as an appropriate choice since it provides a large surface area with its extended fins; however, the enormous amount of flue gas needed to be cooled meant this was not a feasible design.

This leaves us with the tubular type heat exchangers. Among the many types of tubular heat exchangers, the shell-and-tube provides the best surface-to-volume ratio. Furthermore, shell-and-tube exchangers are flexible in their designs and can withstand high pressure conditions. However, to save costs, we've decided to go with a compact shell-and-tube heat exchanger, which is simply a hybrid of the concepts from a shell-and-tube type heat exchanger and an air-cooled condenser. A compact shell-and-tube heat exchanger is basically a shell-and-tube heat exchanger whereby the outer surfaces of the tubes are extended using fins. This can generally result in an increase in surface area by about 15-20 times. The compact shell-and-tube heat exchanger is one in which the amount of heat transfer has been maximized for a given size heat exchanger.

Next, there are many factors to take into account when dealing with shell-and-tube type heat exchangers. First, we had to decide where should the flue gas stream flow. This was easily determined using a basic approximation ($h_iA_i \approx h_oA_o$) Since the heat transfer coefficients of gasses are generally much lower than that for liquids, the area needed for the gas side would be much larger and thus, the flue gas should flow through the shell while the cooling water should flow through the tubes. Besides that, the water in the flue gas will be condensing. Having the flue gas outside the tubes would allow for an easier procurement of the water. Furthermore, an enormous pressure would be needed to compress the flue gas through the small tubes and this would increase significant operational costs. The bundled tubes should be arranged in a staggered form to increase contact area with the flue gas. This also reduces by-pass of the flue gas without an efficient heat transfer. The flue gas stream and the water stream should observe a counter-flow arrangement as it is the most efficient when comparing heat transfer rate per unit surface area. Also, a counter-flow arrangement provides a more uniform temperature difference across the heat exchanger, thus minimizing thermal stress, extending the life of the heat exchanger.

The next thing we had to do was to calculate the total surface area needed. This was calculated using the basic heat transfer equation ($Q=UA\Delta T$). As discussed earlier, heat was calculated using HYSYS. As for the overall heat transfer coefficient, we assumed a value for an air-cooled heat exchanger used for cooling water[1]. Then, the total fan power required is also estimated using a correlation[1] generally used for air coolers. To calculate the pump power required, we had to make several assumptions. The length of the tubes is assumed to be 40 feet as this length is the general maximum length published by many sources. Tube outer diameter was estimated to be 2.38 inches arbitrarily from a given set of industrial tube diameters found. From these set tube parameters, the total pressure drop across the tubes are calculated using basic fluid mechanics knowledge. This in turn gives us the pressure required by the pumps and thus the power.

Next up, we can finally calculate the capital cost of our heat exchanger and the operational costs of the pumps and fans used. The capital cost was estimated using a correlation for an air-cooler found in Seider's design book[2]. This number was then corrected to current year value using the CE index found in the Chemical Engineering journal. The capital costs for the pumps and fans were neglected as it is believed to be negligible compared to the cost of the heat exchanger. Then, the operating costs for the pumps and fans were calculated using the given power rate of $0.07/kWh.

5. Team Structure and Assignments

A. *Team member's skills and experience*

First	Last	Major/ Minor	Skills and Strengths	Relevant Coursework Pertaining to Project
Don	Dornbusch	ChE	Matlab, Polymath, Excel, C++, Hysys, Labview	Fluid Mechanics Heat and Mass-Transfer Thermodynamics Transport Phenomena Modeling
McLain	Hubbard	ME	MATLAB, ProE, Solidworks, Excel	Fluid Dynamics Compressible Flow Thermodynamics Heat Transfer and Thermal Systems
Sajid Ali	Khan	MMAE	Matlab	Thermodynamics Fluid Mechanics Heat Transfer
Alexander	Kolbasov	ME	Matlab	
David	Malon	ChE	Matlab, Labview, Hysys, Excel, C++	Material and Energy Balances Fluid Mechanics Heat and Mass-Transfer Physical Chemistry
Wai Kit	Ong	ChE	Matlab, Labview, Hysys, C++	Fluid Mechanics Heat and Mass Transfer Thermodynamics Statistical Tools for Engineers Physical Chemistry Economic Analysis and Capital Investments
Jesse	Reinhardt	BioChem	Excel, Word, Powerpoint, C++	Analytical Chemistry Biochemistry

Sithambara Kuhan	Sivanyanam Pillai	ChE	Excel, Word, Powerpoint, LabView	IPRO CO2 Mitigation: A Techno-Economic Assessment Heat and Mass-Transfer Operations Statistical Tools for Engineers Thermodynamics I Economic Analysis and Capital Investments Fluid Mechanics
Kwong Hann	Tan	MMAE	Matlab, Autocad, Excel, Adobe Photoshop	Computational Mechanics Thermodynamics and Applied Thermodynamics

B. *Team Structure*

The original Team Structure was not changed much as the semester progressed. The only changes occurred for budget managing, which was overseen by Jesse, and work on deliverables such as IPRO day preparation and the Final Report, which most Team members came together to work on.

Group I: Direct Contact Cooling

Don — IPRO Team Leader -Serves as a liaison between Groups and composes class-meeting agenda for the Team which includes deliverables and tasks within each Group.
Kuhan — Research
Jesse — Group Recorder - Records meeting decisions and is responsible for deliverable materials (i.e. calculation copies, simulation files, uploading files). Also in charge of managing the Team budget.
Alex — Group Leader - Schedules tasks for each team member, ensures group is up to date with deliverables.
Siyed — Research

Group II: Indirect Contact Cooling

McClain — Research
Wai-Kit — Research
Kwong — Group Recorder - Records meeting decisions and is responsible for deliverable materials (i.e. calculation copies, simulation files, uploading files).
David — Group Leader - Schedules tasks for each team member, ensures group is up to date with deliverables.

6. Project Budget

Item	Price	QTY	Total	Purpose

Group meetings	$44.00	2	$88.00	Covered the cost of pizza and soda drinks when we met to work on the project outside of class on 10/23 and 11/26.
	$24.00	1	$24.00	Covered the cost of Chinese food and soda drinks when we met to work on the project outside of class on 12/6.
Perry's Chemical Engineers' Handbook, Eighth Edition (Chemical Engineers Handbook) (Hardcover)	$103.56	1	$103.56	For research
Total			$215.56	

7. Results

Based on the sponsors' data, we were able to determine specific parameters that are required prior to designing the water recovery systems. We first determined the composition of the flue gas based on a combustion analysis, results of which are displayed in the following table.

Composition	Mass Flow Rate (kg/s)	Mass Fraction
CO_2	202.9047	0.189199
H_2O	74.4187	0.069392
O_2	55.91942	0.052142
N_2	723.8174	0.674926
SO_2	2.149987	0.002005
Ar	13.21852	0.012326
Cl	0.010761	1.00E-05

With the flue gas being cooled from 130°F to 100°F, we determined that a maximum of approximately 270,000 kg/h of water could be recovered from the flue gas.

Direct Contact

Once the flue gas compositions and conditions were determined, the simple spray tower design was chosen. The following is a schematic diagram representing the cooling-condensing spray tower.

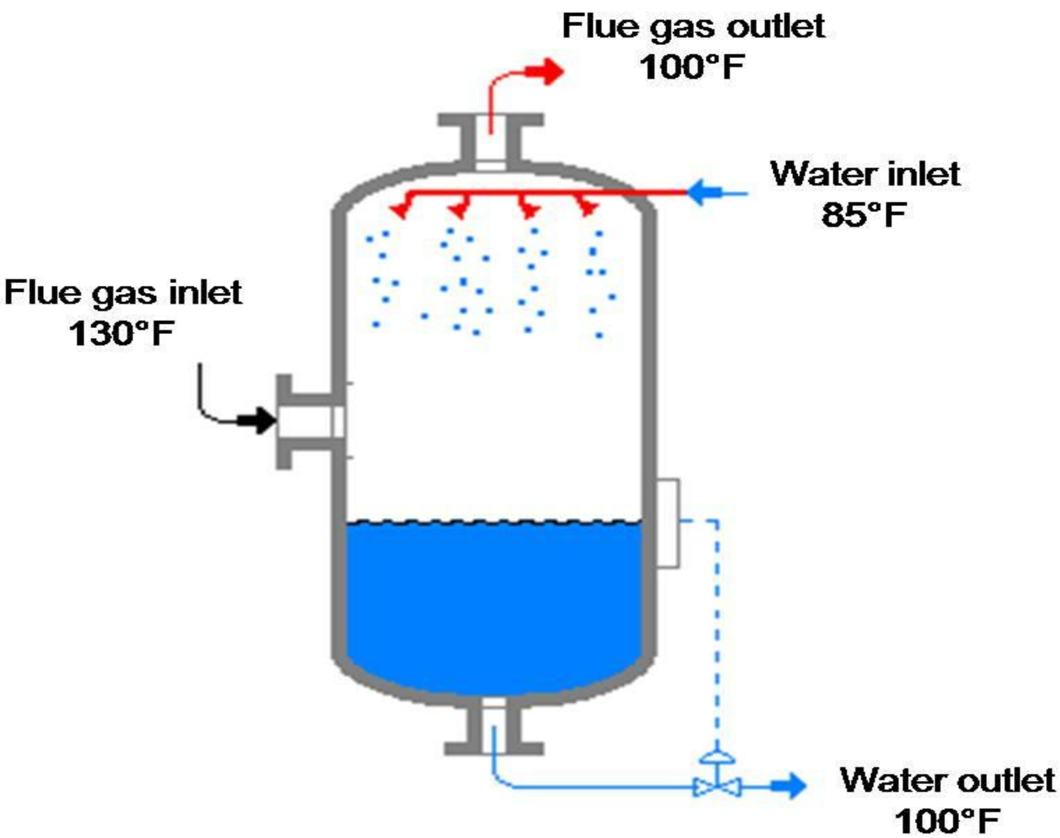


Figure 1: Schematic of simple spray tower design

The saturated flue gas enters the tower at a 130°F. It comes in direct contact with water being sprayed down from high-pressure spray nozzles at 85°F. As the hot flue gas moves upwards along the tower due to its low density and buoyant forces, the tiny water droplets condense the water vapor within the flue gas as its temperature drops. Water droplets, which are denser, would naturally be collected at the bottom of the tower. Both the water and flue gas exit the spray tower at 100°F. The water is then sent to an auxiliary cooling system (most probably a cooling tower used for cooling of the boiler feed water), before a part of this flow is re-circulated back into the spray tower.

The following table outlines the important design parameters of our spray tower system, and the total capital and operational costs we estimated.

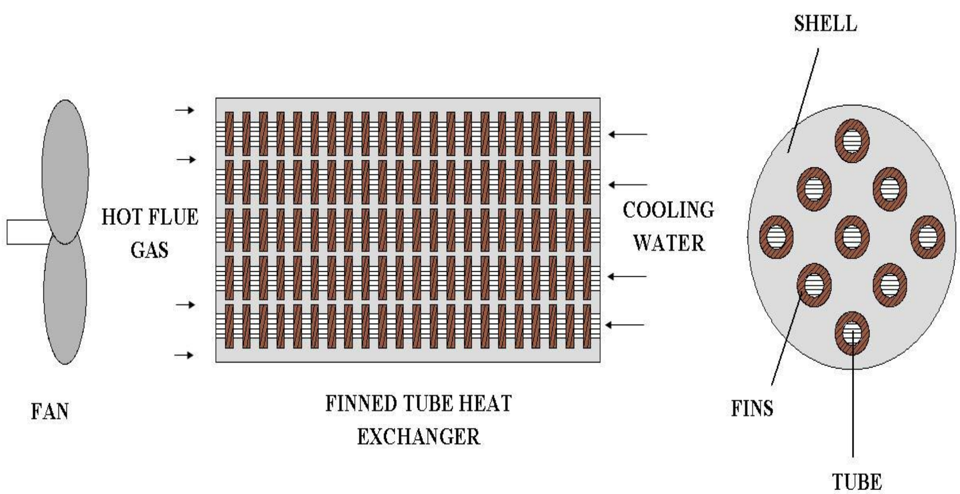
Part	**Parameter**	
Tower	Height	7 meters

	Diameter	2 meters
	Primary Material for Construction	Carbon Steel
Nozzles	Type	Flat cone
	Droplet diameter	750 microns
	Operating flow rate	9,000 gpm/nozzle
	Operating pressure	470 psi
Pump	Type	Condensate pump
	Total flow rate	90,000 gpm
	Power requirements	9,000 HP
Cost		
Capital Cost	**US$ 218,000**	
Annual Operating Cost	**US$ 3,273,000**	

Table 1: Design parameters for spray tower and costs

Indirect Contact

Once the flue gas compositions and conditions were determined, the heat exchanger design was chosen. The following is a schematic diagram representing the compact shell-and-tube heat exchanger.



The saturated flue gas enters the shell-side of the heat exchanger at 130 °F while cooling water flows through the tubes at 85 °F. Both streams are set to leave the heat exchanger at 100 °F. Cooling the flue gas to this temperature would allow us to recover about 74.1 kg/s of water. The heated water is then sent to a cooling system (an air cooler or a cooling tower) and cooled back to about 85 °F before being re-circulated back into the heat exchanger.

The following table outlines the important design parameters of our heat exchanger system, and the total capital and operational costs we estimated.

	Shell-side		**Tube-side**	
Fluid	Flue Gas		Water	
Total Flow [kg/h]	4018000		20124000	
Vapor (in/out)[kg/h]	4018000	3750000	0	0
Liquid (in/out)[kg/h]	0	268000	20124000	20124000
Temperature (in/out)[^{0}F]	130	100	85	100
Heat Duty [kJ/h]	7235000			
Area [m^2]	27000			
Capital Cost [US$]	837000			
Operating Equipments	Fan		Pump	
Power Requirement [kW]	4320		678	
Annual Operating Cost [US$]	2650000		416000	

Based on a comparison of the annualized costs and ultimately the costs of recovering 1000 gallons of water, the indirect contact method was determined to be marginally better in terms of economics. However, it needs to be noted that there are a number of costs that we were unable to effectively determine could tip the scales on this comparison, a prominent one being maintenance costs against fouling and corrosion within the systems. To obtain a better understanding of the economic feasibility of our designs, we compared our costs to the average water premium in various developed nations. The following diagram outlines this comparison.

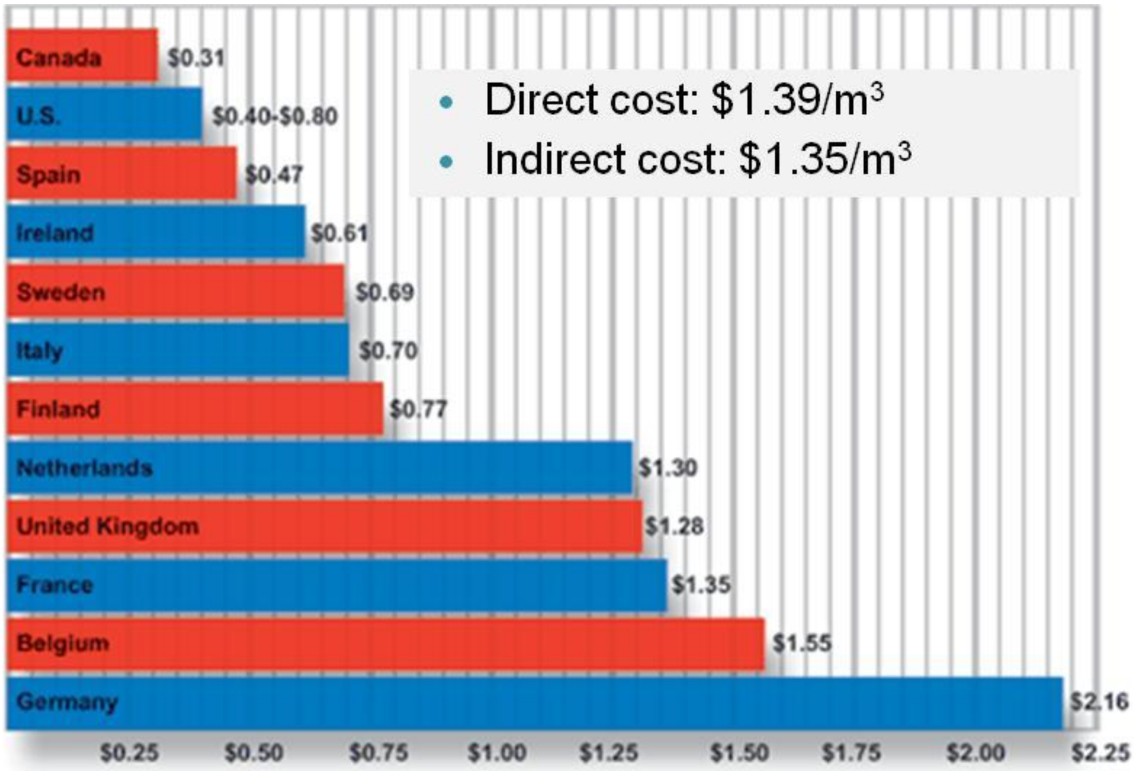


Figure 4: Typical prices of water across developed countries (Adapted from Environmental Canada, 2008)

Thus, it is seen that based on our current estimated costs, the water recovery method is not economically feasible on average in many developed countries, as it would be cheaper to purchase municipal water and feed it into the pollution control systems. However, it is important to note that water can be a scarce resource at some sites, or there may be environmental regulations that restrict the amount of water the power plant can consume. In such situations, our proposed designs would prove more appealing.

8. Obstacles

A. Our Team needed estimates for the spray tower and water pumps, but we received very few responses back from companies.

Direct Contact

a) There were a number of obstacles with regards to the design of the spray tower, the most prominent being the wide array of variables the design team needed to deal with. It was difficult to decide on a certain parameter, as we had minimal knowledge on the actual impact of the assumptions we made with regards to these variables. This leads us to our second major obstacle in this project – the lack of literature to compare our assumptions with. Spray tower designs have been used for decades, yet there are very limited literatures for theoretical sizing of these spray towers. Another noteworthy point is the fact that spray systems in current times are primarily used for pollution control systems rather than for cooling purposes, as required for our project.

b) Our power plant's lack of tolerance to pressure drops provided massive limitations to our project, as we could not consider more efficient direct contact designs such as packed columns or tray towers. We were also unable to fit in equipment such as demisters to improve the efficiency of the condensation process within the tower.

Indirect contact

a. For the calculation of the total surface area needed to transfer the total amount of heat for recovering water, we needed to determine the overall heat transfer coefficient. This proved to be a roadblock due to the complexity of the flue gas and the heat exchanger design. With that down, we were able to determine the heat transfer area required.
b. The other huge obstacle that we had to face was the sizing of the heat exchanger. With the limited information that we had, it was difficult to determine the parameters of the tubes and fins of our heat exchanger.

B. By calling the companies, instead of emailing, our chances of getting an estimate increased. By contacting the companies in a nice and friendly manner, some of our contacts could be revisited to help in more than one instance.

Indirect contact

a) To proceed with the research, we assumed a value for an air-cooled heat exchanger used for cooling water. This was found to be a reasonable assumption because flue gas and air have very similar heat transfer coefficients. Also, this air-cooled heat exchanger is essentially a water-air heat exchanger with finned-tubes, just like our model.
b. We arbitrarily chose a commonly-found pipe diameter and thickness. The length chosen is the maximum length found for industrial pipes. These are used to find the pressure drop of water in the pipes. Fin parameters are not defined as correlation based on an air cooler was used.

C. *Indirect contact*

a) We could have contacted our sponsor, Sargent and Lundy, to obtain more specific information and rules of thumbs for our heat exchanger design.

b) We could have also spent more time looking through available literature that would give estimations for our project.

D. Other designs for processes such as membranes, desiccants, and refrigeration still need to be researched more thoroughly;

9. Recommendations

Based on our conclusions, it is clear that there are still major economic barriers that go with the implementation of our designs. Thus, there is still a wide prospect of future growth working on this project. There are other technologies other than this we have looked at in this project which we were unable to study in more detail due to time constraints. Some of the new technologies that show promise for the future include membrane and desiccant separation systems.
There is also more improvement of our current-proposed designs, and such improvements can ultimately reduce our current estimated costs, making them more economically appealing.

10. References

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11. Resources

Individual hours spent on accomplishing parts of the project can be found on iGroups.

12. Acknowledgements

Bill Griffiths – An Independent Consultant for Humidity Control Consulting
Contributions:

- Provided us with a rough spray tower design and cost estimate ($30-50 million)
- Recommended us getting multiple pumps to increase the reliability of the system

- Provided us with a PSI output of 22-26 that we used to get water pump estimates with

Bruce Currie - Sales Engineer for Superior Industrial Equipment
Contributions:

- Provided us with a detailed quotation for a 4000 GPM, 75 HP water pump ($25,742.00)

Jeff – www.PumpBiz.com
Contributions:

- Provided us with a 4000 GPM, 50 HP water pump estimate ($9,000.00)

Industrial Process Equipment
Contributions:

- Provided us with a 4000 GPM, 75 HP water pump estimate ($17,000.00)

Kelli Steele – Sundyne Corporation, Sine Pump Division
Contributions:

- Confirmed the conversion: 2.31 psi = 1 ft of head

Mark Kramer – Head engineer for Merom Power Plant
Contributions:

- Recommended different types and sizes of pipes that we could use